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The effects of starter fertilizer on root and shoot growth of corn hybrids and seeding rates and plant-to-plant variability in growth and grain yield

Warren Pierson
Iowa State University

The effects of starter fertilizer on root and shoot growth of corn hybrids and seeding rates and plant-to-plant variability in growth and grain yield

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Warren Lee Pierson

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Program of Study Committee:
Roger W. Elmore, Co-major Professor
Mary H. Wiedenhoeft, Co-major Professor
Antonio P. Mallarino

Iowa State University

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CHAPTER 1: GENERAL INTRODUCTION

Starter fertilizer (SF) often increases early-season growth and reduces time to maturity for corn (*Zea mays* L.) (Bermudez and Mallarino, 2002; Bullock et al., 1993). Effects of starter fertilizer on corn grain yield have varied with some researchers finding that hybrids responded differently to starter fertilizer application (Gordon et al., 1997), while others have found that hybrids responded similarly (Buah et al., 1999). Agronomists that found differences in hybrids response to starter fertilizer also found that the root systems of hybrids that responded to SF were generally smaller than those that did not respond to SF (Gordon and Pierzynski, 2006; Rhoads and Wright, 1998). Many farmers in central Iowa abandoned SF applications due to the cost and weight of placement units, costs associated with handling the fertilizer, and lack of grain yield responses in their fields.

Plant-to-plant variability in corn growth and grain yield is often associated with reduced grain yield (Muldoon and Daynard, 1981). Increased variability in growth is often associated with plant spacing standard deviation, however, grain yield responses to plant spacing uniformity are variable. While some researchers have found that reduced plant spacing standard deviation increases yield (Nielson, 2001), others have found that plant spacing is not important in grain yield (Liu et al., 2004b). Variability in emergence is important in final yield and agronomists have developed recommendations for replanting based on variation in emergence within a field (Liu et al., 2004a; Nafziger et al., 1991). Uniformity in seeding depth and soil factors such as moisture, temperature, residue cover, and crusting often affect uniformity in plant emergence (Alessi and Power, 1971; Nafziger et al., 1991).

Farmers ask if starter fertilizer could reduce variability in early-season growth in cool and wet soils often associated with high residue situations. They reason that uniform nutrient availability to corn seedlings may reduce plant-to-plant variability in growth and grain yield. Reducing plant-to-plant variability in growth and development is a goal of high-management producers and tools to reduce variability in growth and grain yield will be important in the future. The effects of starter fertilizer on plant-to-plant variability in growth have not been studied to our knowledge.

Thesis Organization

This thesis is organized in the journal manuscript format with five chapters. Chapter 1 is a general introduction and description of the thesis format with literature cited at the end. Chapter 2 is a manuscript evaluating three hybrids, three seeding rates, and with and without starter fertilizer effects on growth, development, and grain yield of corn. Chapter 3 assesses root characteristics associated with hybrids in response to three seeding rates with and without starter fertilizer utilizing scanner-based technology to evaluate corn seedling roots. Chapter 4 documents hybrid responses to seeding rates and starter fertilizer on plant-to-plant variability in growth and grain yield. The effects of plant-to-plant variability in growth and grain yield are then correlated to total grain yield ha^{-1}. Chapter 5 is a general conclusion of all manuscripts included in this thesis. Literature cited for chapter is included at the end of each chapter. An appendix with averages of four replications of measurements performed separated by treatment is included after Chapter 5.

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CHAPTER 2: EFFECT OF STARTER FERTILIZER ON GROWTH, DEVELOPMENT, AND GRAIN YIELD OF CORN HYBRIDS AND SEEDING RATES

A paper in preparation for *Agronomy Journal*

Abstract

Starter fertilizer (SF) often increases early-season growth and the developmental rate of corn (*Zea mays* L.), while yield responses have varied. One objective of this study was to identify how seeding rates and hybrids with different root ratings respond to SF in growth, development, and grain yield. Another objective was to identify why grain yield responses to SF have been variable. Two similar experiments were conducted at Ames, IA and Nashua, IA in 2011 and 2012; locations differed in tillage and crop rotation. We used three hybrids, three seeding rates, and with and without SF as treatments to create different stresses for corn plants. We measured developmental stage, plant heights, stem diameters, and destructively sampled for biomass to create models to estimate plant size on plants that were eventually hand harvested; grain yield components were measured. Grain yield and moisture were measured at harvest. Starter fertilizer increased estimated plant biomass at 8 of 12 sample dates at Ames, IA and 4 of 6 sample dates at Nashua, IA. Developmental stage increased at 8 of 9 sample dates at Ames, IA and 3 of 4 sample dates at Nashua, IA with SF. Starter fertilizer increased kernel row number plant^{-1} in 2012 – a drought year – at both locations. Starter fertilizer application had no impact on grain yield in 2011. However, application of SF increased grain yield by 0.79 Mg·ha^{-1} at Ames in 2012 and increased yield at Nashua in 2012 at the low and medium seeding rates by 1.17 Mg·ha^{-1} and 1.58 Mg·ha^{-1} respectively. Lack of yield response to SF at the high seeding rate at Nashua was likely related to moisture

stress impacting the higher seeding rate more severely. Starter fertilizer may be a tool for farmers to expedite developmental rate of corn and economically and efficiently increase grain yield in fields with high nutrient spatial variability.

Introduction

Corn hybrids are rated for characteristics such as disease tolerance, root strength ratings, cumulative relative maturity, and stalk strength in order for farmers to match hybrid characteristics with field characteristics. Seed companies also often recommend different seeding rates for hybrids for optimum economic return. Changes in seeding rates for hybrids may affect growth, development, and grain yield responses to agronomic inputs such as SF application.

With cold soils, starter fertilizer often increases early growth and development of corn, however, SF also improves early growth and development to a lesser degree with warmer soils at later planting dates (Cromley et al., 2006). Early-season growth responses to SF occurred on soils with high P soil tests with larger responses on soils with low soil P tests (Bermudez and Mallarino, 2002). Plant dry weights were greater with SF than without between 400 and 500 growing degree days (GDDs) in two different years and remained that way until approximately 1200 GDDs (Bullock et al., 1993). Starter fertilizer also increased developmental rate of corn; plots receiving SF tasseled and reached black layer approximately 2 – 3 days earlier than those without, and also had lower grain moisture content at harvest (Bullock et al., 1993). Researchers found that the time from emergence to silking varied by hybrid in response to SF (Gordon and Pierzynski, 2006) and others found that hybrids with longer maturities responded to SF more than those with shorter maturities (Cromley et al., 2006). Starter fertilizer reduced days to silking for earlier planting dates more than later planting dates (Cromley et al., 2006). Although treatments receiving SF reached reproductive stages earlier, SF did not affect the grain fill period or rate of assimilation during grain fill (Bullock et al., 1993).

Although SF often increases early-season growth, grain yield responses are variable. Bullock et al. (1993) saw no yield response to SF and suggested that it was due to the SF having no effect on final plant size. Utilizing a tillage by SF experiment, Bermudez and Mallarino (2004) found yield responses to SF were small, infrequent, and not affected by tillage. A study comparing SF formulations (3-8-15 and 0-0-25 N-P-K) in addition to broadcast P-K fertilizer spread 1–15 days before planting, showed that SF increased early-season growth and early-season nutrient uptake compared to broadcast only, however, yield was not affected (Mallarino et al., 2011). A similar study showed that P-K SF applied at one-eighth the rate of P-K broadcast fertilizer produced similar yield as the broadcast fertilizer at four of nine locations that responded to fertilization (Kaiser et al., 2005). These authors indicated that early corn growth and nutrient uptake responses to SF were not reliable indicators of grain yield responses.

In contrast to these studies, many scientists have found yield responses to SF, even on fields with high nutrient soil tests. Starter fertilizer increased grain yield economically on fields with high soil fertility and when hybrids with longer relative maturity were planted at later planting dates in Wisconsin (Bundy and Andraski, 1999). Research conducted using global positioning systems (GPS) and geographical information systems (GIS) showed that increased early growth was positively, but poorly correlated to a 2.4% yield response (Bermudez and Mallarino, 2002). An Iowa study reported that SF increased grain yields in seven of nine site-years, and the 12 hybrids included in the study responded the same to SF

(Buah et al., 1999). In contrast to this, studies conducted in Florida found hybrids varied in their early-season growth response to SF (Teare and Wright, 1990). Agronomists in Kansas also reported that hybrids varied in their grain yield response to SF (Gordon et al., 1997; Gordon and Pierzynski, 2006). Some suggest that SF may be useful when soil tests are low, soil moisture is limiting, and if fertilizer efficiency and economic returns are to be optimized (Randall and Hoeft, 1988). Others recommend SF for soils with conservation tillage or no tillage and that the probability of grain yield returns to SF decreases as tillage increases (Touchton and Karim, 1986).

Growth and development of corn are not synonymous; growth refers to an increase in size of a plant size and development refers to a plant's progression to maturity (Abendroth et al., 2011). Bullock et al., (1993) found that plants progressed through development faster with SF, however, plant leaf area index (LAI) and LAI duration – both measures of growth - were not altered by SF.

Grain yield is negatively affected by environmental stress during the time bracketing silking (Westgate et al., 2004). Breeders have selected for hybrids with less temporal separation between silking and anthesis; a short anthesis-silking interval (ASI) is considered best for kernel set (Bolanos and Edmeades, 1993; Bolanos and Edmeades, 1996; Tollenaar and Wu, 1999). Others have found hybrid and seeding rate responses to nitrogen fertility rates while measuring growth parameters such as plant height, stem diameter, and grain yield (Boomsma et al., 2009). These researchers also studied developmental parameters such as ASI in response to hybrid, seeding rate and nitrogen rates. In those studies, increasing seeding rates resulted in reduced plant size and grain yield plant^{-1}, while ASI generally increased (Boomsma et al., 2009).

Many farmers no longer apply SF due to application costs, additional time required at planting, additional costs of SF transportation, and perceived lack of responses to SF. Yet many are reconsidering this decision because of high residue which causes cool and wet soils in continuous corn fields, as well as today's higher value crops. As mentioned above, research regarding SF grain yield responses has varied. Increased early-season growth associated with SF is common, but the factors affecting these grain yield responses are unclear. Research has focused on hybrid, soil texture, tillage, and fertilizer content. To our knowledge, no SF studies related to either seeding rate or hybrids with reported differences in rooting ability have been conducted. The objectives of this study were to determine effects of SF on growth, development, and grain yield of corn for several hybrids with reported differences in rooting ability at different seeding rates to see if SF affects hybrid and seeding rate responses.

Materials and Methods

Treatments

We conducted field experiments at the Agricultural Engineering and Agronomy Farm near Ames, IA during 2011 and 2012. Plots were located at 42° 01´ 55" N, 93° 78´ 72" W, on a Clarion loam soil with 2 to 5% slope in 2011 and 42° 01´ 07" N, 93° 73´ 97" W on 41% Canisteo silty clay loam and 37% Clarion loam soil with 0 to 2% slopes in 2012. Plots were moved in 2012 so plots with SF applied in 2011 would not affect yield responses in 2012. We planted plots on 4 May 2011 and 26 April 2012. Corn was the previous crop in both years, and tillage consisted of one-pass fall chisel plow and one-pass spring field cultivation. Plots were 15.2 m long and consisted of six, 0.76 m rows planted with a Kinze planter using chain driven finger pickup meters. The planter was equipped with fixed row cleaners - set to remove residue but not plow into the soil - and a liquid SF applicator using angled coulters to place fertilizer 5 cm below and 5 cm to the side of the seed (5×5). The experimental design was a randomized completed block with treatments arranged in a complete factorial and replicated four times. Treatments included 3 seeding rates (74.1, 88.9, and 103.7×10^3 seeds$\times$ha^{-1}), 3 DuPont Pioneer hybrids (P0448XR, P0461XR, and P0463XR), and with and without SF. We used a liquid SF treatment consisting of 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg$\cdot$ha^{-1}. Nitrogen (N) was applied post emergence as 28% urea ammonium nitrate at a rate of 224.1 kg$\cdot$ha^{-1} at approximately V4 to all plots (Abendroth et al, 2011). We applied more N than recommended by Iowa State University Extension so that the N in the SF would not increase yield due to fertility limitations in the non- fertilized plots (Iowa State University, 2013).

Field experiments were also conducted at the Northeast Research and Demonstration Farm near Nashua, IA during 2011 and 2012. Plots were located at 42° 92′ 97” N, 92° 57′ 63” W in 2011 and 42° 93′ 05” N, 92° 57′ 68” W in 2012 on Floyd loam soils with 1 to 4 % slopes. We planted the experiments on 13 April 2011 and 24 April 2012. In both years, soybean was the previous crop, and no tillage was performed prior to planting. Plots were planted with a planter equipped with fixed row cleaners set to remove residue and plow slightly into the soil to remove loose soil for greater seed to soil contact and a dry SF applicator using angled coulters to place fertilizer 5 cm below and 5 cm to the side of the seed (5×5). The dry fertilizer treatment was 11-52-0 (monoammonium phosphate) applied at a rate of 112.1 kg$\cdot$ha^{-1}. Nitrogen was applied before planting as anhydrous ammonia at a rate of 157 kg$\cdot$ha^{-1} N. Hybrids and seeding rates were the same as those used at the Ames location.

Herbicides included both pre- and post-plant chosen based on Iowa State University Extension recommendations. Hybrids provided by DuPont Pioneer International (Johnston, IA) included P0448XR, P0461XR, and P0463XR and will be referred to as hybrid 1, 2 and 3 respectively from here on. Hybrids had similar relative maturities, 104, 104, and 103 for hybrids 1, 2, and 3, respectively, and were commonly grown in IA. Hybrids were chosen to include a range of root strength ratings assigned by the seed company: 7, 8, and 5 for hybrids 1, 2, and 3, respectively. Root strength ratings were determined by visually measuring standability after mechanical wind damage was performed. These ratings are scaled 1- 9 with 1 being the least and 9 being the strongest. Seeding rates were 74.1, 88.9, and 103.7 × 10^3 seeds·ha^{-1}. Soil samples were taken from 0 to 15 cm in each replication before planting and postharvest.

Biomass Data Collection

We tagged several plants and compared them to measurements of non-tagged plants to estimate biomass. Tagged plants included five consecutive plants in rows four and five (10 total) of each plot. To identify tagged plants, we placed a stake between rows four and five, 3.3 m from the plot border and another stake 4.5 m from the same plot border; plants between these stakes were marked with date of emergence noted on individual stakes. We checked plots daily for emergence from 5 to 20 days after planting. We recorded early-season plant populations until stand counts were the same for multiple days and late-season plant populations after R6 but before harvest. Plant spacing was recorded on tagged plants and spacing standard deviation calculated for each plot.

After all plants emerged, we marked the first five consecutive plants between the 3.3 m and 4.5 m stakes with numbered stakes, recorded emergence date, and hence forth considered these plants tagged plants. These tagged plants were measured throughout the season for biomass estimates. Our untagged plants consisted of six groups of randomly selected plants. Each group of five consecutive untagged plants were in row two and were as evenly spaced as possible, with intact plants between them, to ensure removal of the untagged plants would not impact growth of other groups to be harvested later. We used untagged plants as proxies for in-season biomass estimates of the tagged plants. Tagged and untagged plants were staged during vegetative growth using a modified version of the Iowa State University leaf collar method (Abendroth et al., 2011). This modification allowed us to stage plants to 0.25 accuracy; we did this at approximately V4, V6, V9, and V15 in 2011 and V2, V4, V6, V9, and V15 in 2012. Accumulated GDD at each sampling date are recorded in Table 2.

The 5th and 10th leaf were painted on all tagged and untagged plants to allow for accurate staging after the lower leaves senesced and decomposed due to stalk expansion (Abendroth et al., 2011). Plant heights for tagged and untagged plants were measured using the ‘extended-leaf method’ in which each plant is measured from soil to the tip of the uppermost fully extended leaf at V2, V4, V6, V9, V15, and R2 at Ames and V3, V9, and R2 at Nashua. We also measured stem diameter of both tagged and untagged plants on the widest part of the elliptical stalk with a digital electronic caliper approximately 1.25 cm above soil level at V2, V4, and V6 and at a location centered between the 7th and 8th node at V9, V15, and R2; these measurements were taken at similar locations at Nashua at V3, V9, and R2. We chose to measure between the 7th and 8th node, which varies in height above soil over time, approximately 8 cm above soil surface, to avoid above-ground nodal roots restricting late season measurements.

Untagged plants were cut at the soil surface at V2, V4, V6, V9, V15 and R2 and placed in a marked bag. Plants were oven dried at 60 °C until constant weights were attained, and biomass measurements were recorded per plant. Total leaf number was counted on tagged plants after all leafs emerged. Tagged plants were checked daily during silking and anthesis to measure ASI at Ames, IA. Silking was determined as the date of the first silk emerging from husk leaves and anthesis was determined as the date of pollen anthers shedding pollen (Abendroth et al., 2011). After silking, the distance between tagged plants was measured and plant spacing standard deviation calculated per plot.

Plant Biomass Estimate Equations

Biomass equations (Table 2) were developed for each sampling date by correlating plant height and stem diameter measurements to biomass of destructively sampled untagged plants to be able to estimate the biomass of tagged plants. Stem diameter was plotted against destructively sampled plant biomass and correlated to biomass in both linear and quadratic relationships. We used both linear and quadratic equations for stem diameter because generally both were similarly correlated and added strength to our model. Plant height was also plotted against destructively sampled plant biomass and correlated to biomass in a linear relationship. We included plant height as a linear function in our equation and stem diameter as both linear and quadratic functions due to these relationships. The PROC REG procedure of SAS software package, version 9.2 (SAS Institute, 2010) was used to develop equation parameters (Table 2). The equations developed appear as:

$$\text{Biomass} = x\,(\text{plant height}) + y\,(\text{stem diameter}) + z\,(\text{stem diameter})^2 + \text{intercept}$$

These equations were used to estimate the biomass at each sampling date of “tagged plants”.

Grain Yield Data Collection

We hand harvested individual ears after random samples from border rows had reached physiological maturity. Physiological maturity was determined by checking plots until all randomly selected ears kernels had black layer and ready for hand harvest of tagged plants. We husked the hand harvested ears and counted the number of kernel rows per ear. In 2011, ears were hand shelled, while in 2012 a mechanical sheller was used; we recorded wet grain weight immediately after ears were shelled. We then oven-dried grain at 60 °C until constant weights were attained, and recorded dry grain weight per plant. Grain yield from individually harvested plants was converted to 155 $g \cdot kg^{-1}$ moisture. We collected yield and moisture using a plot combine, and then converted to 155 $g \cdot kg^{-1}$ moisture. Yield from individually harvested plants was added to the yield that was combine-harvested to obtain final plot yield. Kernel number per plant was measured using a The Old Mill Company Model 850-2 electronic seed counter (International Marketing and Design Corp, San Antonio, Texas).

Statistical Analysis

Analysis of variance was performed using the PROC MIXED procedure of the SAS software package, version 9.2 (SAS Institute, Cary, NC). Treatments were considered different when $P \leq 0.05$. Tagged plants were considered random; tagged plants that died throughout the season were treated as missing values. Treatment differences were separated using the lsmeans statement of the PROC MIXED procedure of SAS (SAS institute, Cary, NC). Experiments were analyzed separately due to differences in tillage, fertilizer, and crop rotation. Years were analyzed separately due to differences in weather patterns. All treatment factors were considered fixed, including SF, population density, and hybrid, whereas replications were treated as random.

Results

Ames, Iowa

Phosphorus soil tests were optimum to high in 2011 and very low to low in 2012 (Sawyer et al., 2002). Both years accumulated less precipitation than the 26-year average (Figure 1). In 2011, growing degree days accumulated less than the 26-year average while in 2012, growing degree day accumulation was more than the 26-year average (Figure 2). Early- and late-season stand counts were strongly correlated with the seeding rates in both years. Late- season seeding rates in 2011 averaged 1,482 less plants per hectare when SF (SF) was applied. In 2011, a hybrid by seeding rate interaction occurred for spacing standard deviation; hybrid 2 had ≥ 42% larger spacing standard deviation than the other seeding rates at 74.1×10^3 seeds·ha^{-1}. In 2012, seeding rate was related to spacing standard deviation; the 74.1×10^3 seeds·ha^{-1} seeding rate had higher spacing standard deviation than seeding rates of either 88.9 or 103.7×10^3 seeds·ha^{-1}. Late- season stand counts were not affected by hybrid ($P = 0.1784$) but were affected by seeding rate ($P < 0.0001$) while a hybrid and seeding rate interaction occurred at ($P = 0.0659$); hybrids averaged different stand counts at different seeding rates (data not shown).

Starter fertilizer increased plant biomass by 26%, 21%, and 13% at the V4, V6, and V9 samplings, respectively, in 2011 (Table 3). In 2012, SF increased plant size by 15%, 23%, 24%, 18%, and 16% at the V2, V4, V6, V9, and V15 stages, respectively (Table 3). Estimated individual plant biomass was similar at R2 for both SF treatments in both years (Table 3). Hybrid 2 had less biomass than both hybrids 1 and 3 in 2011 from V2 to V6. At

V9, hybrid 1 had greater biomass than hybrids 2 and 3; at V15 and R2, hybrid plant size was not different among the hybrids (Table 3). In 2012, hybrid 1 had greater biomass than hybrids 2 and 3 from V2 to V6 (Table 3). Hybrid 2 had less biomass than hybrid 1 at V9 in 2012; at V15 and R2 stages, hybrids did not differ in individual plant biomass (Table 3). Seeding rate did not affect emergence or V2 biomass (Table 3). However, after V2 in 2011, the lowest seeding rate of 74.1×10^3 seeds·ha^{-1} had greater biomass than the higher seeding rates of 88.9 and 103.7×10^3 seeds·ha^{-1} (Table 3). Increasing seeding rates resulted in smaller plants at V9, V15, and R2 in 2011 (Table 3). The seeding rate of 74.1×10^3 seeds·ha^{-1} also produced plants with greater biomass than the seeding rate of 88.9×10^3 seeds·ha^{-1} at V6 in 2012. After V6 in 2012, the seeding rate of 74.1×10^3 seeds·ha^{-1} produced larger plants than either of the higher seeding rates (Table 3).

Starter fertilizer had no effect on emergence date in either year (Table 3), however, increased average developmental stage by 5%, 2%, 2%, and 3% at the V4, V6, V9, and V15 sampling dates, respectively, in 2011 and by 5%, 2%, 2%, and 6%, at the V4, V6, V9, and V15 sampling dates, respectively in 2012 (Table 4). Increasing seeding rate from 74.1×10^3 seeds·ha^{-1} to 88.9×10^3 and 103.7×10^3 seeds·ha^{-1} resulted in less developed plants from V4 to V15 in 2011 and from V6 to V15 in 2012 (Table 4). Hybrids varied in development at the V4 sampling; hybrid development arranged in the order of most to least developmental stages was hybrid 1, 2, and 3, respectively in 2011 (Table 4). Hybrid 1 was further developed than hybrid 3 at V6 in 2011; at V9 in 2011 hybrid 3 was less developed than hybrids 1 and 2 (Table 4). At V15 in 2011, hybrid 1 was more developed than hybrids 2 and 3 (Table 4). In 2012, hybrid 3 was less developed than hybrids 1 and 2 at the V4, V6, and V9 samplings, however, hybrids were not different at the V15 sampling (Table 4).

Starter fertilizer hastened silking by 1 day in 2011 and 0.9 days in 2012 (Table 5). Days from planting to anthesis were also reduced with SF by 0.5 days in 2011 and 1.4 days in 2012 (Table 5). Starter fertilizer increased ASI by 0.3 days in 2011, however, reduced ASI by 0.3 days in 2012 (Table 5). Delayed silking and anthesis occurred with each increase in seeding rate in 2011; however, in 2012, increasing seeding rate above 74.1×10^3 seeds ha^{-1} caused later silking (Table 5). Delayed anthesis also occurred for each increase in seeding rate in 2012 (Table 5). Increasing seeding rates resulted in shorter ASI in 2011 but increased ASI in 2012 (Table 5). Hybrids silked at different times and in the order of hybrid 3, 1, and 2 in 2011 and 2012. In 2011, hybrid 3 shed pollen before hybrids 1 and 2, which silked at similar times (Table 5). Hybrid 2 had a shorter ASI than hybrids 1 and 3 in 2011 (Table 5). Hybrids ASI length varied and are organized here in the order from shortest to longest: hybrid 1, 3, and 2 in 2012 (Table 5). A hybrid and seeding rate interaction occurred for ASI in both years in which hybrid responses to increasing seeding rates varied in magnitude of decrease in 2011 and increase in 2012 (Table 6).

Starter fertilizer had no effect on kernel rows ear^{-1} in 2011, however, increased kernel rows ear^{-1} by 1.1 rows ear^{-1} in 2012 (Table 7). Kernel number plant^{-1} was not affected by SF in 2011 but increased by 43 kernels with SF in 2012 (Table 7). Starter fertilizer increased grain yield plant^{-1} 12.2 g in 2012 but not in 2011 (Table 7). Plant moisture at hand harvest was reduced with SF by 1.2 g·kg^{-1} in 2011 and 1.5 g·kg^{-1} in 2012 (Table 7). In 2011, SF had no effect on grain yield ha^{-1}, however, increased grain yield ha^{-1} by 0.79 Mg·ha^{-1} in 2012 (Table 7). Harvest moisture was less with SF in 2012 but was not affected in 2011(Table 7).

Kernel rows ear^{-1} were reduced when seeding rates were increased to 103.7×10^3 seeds·ha^{-1} in 2011(Table 7). In 2012, increasing seeding rate above 74.1×10^3 resulted in fewer kernel rows ear^{-1} (Table 7). Increasing seeding rates reduced kernel number plant^{-1} and grain yield plant^{-1} both years (Table 7). Increasing seeding rate above 74.1×10^3 resulted in greater plant moisture at hand harvest in 2011 (Table 7). In 2011, the highest seeding rate produced the most grain yield ha^{-1}, however the lowest in 2012 (Table 7). Increasing seeding rate from 74.1×10^3 seeds·ha^{-1} to 103.7×10^3 seeds·ha^{-1} resulted in higher harvest moisture in 2012 (Table 7).

Hybrid 2 had the most kernel rows ear^{-1} in 2011, however, the least in 2012 (Table 7). Kernel number plant^{-1} arranged in order from most to least was hybrid 3, 1, and 2 in 2012 (Table 7). Hybrid 2 yield plant^{-1} was less than hybrids 1 and 3 in 2012 (Table 7). Moisture plant^{-1} at hand harvest in 2012 was higher for hybrid 2 compared to hybrids 1 and 3 (Table 7). Hybrid 1 yielded more grain ha^{-1} than hybrid 3 in 2011 (Table 7). Hybrid 2 produced less yield ha^{-1} compared to hybrids 1 and 3 in 2012 (Table 7). Grain moisture was lower at harvest for hybrid 2 compared to hybrids 1 and 3 in 2011 but in 2012 that of hybrid 1 was lower compared to hybrids 2 and 3 (Table 7).

Nashua, Iowa

Phosphorus soil tests were optimum to high in 2011 and low to very low in 2012 (Sawyer et al., 2002). The 2011 growing season accumulated precipitation was similar to the 24-year average, however, in 2012, accumulated precipitation was approximately 21% less than the 24- year average (Figure 3). In 2011, GDDs accumulated similar to the 24- year average while in 2012, growing degree day accumulation was more than the 24- year average (Figure 4). In 2011, early-season stand counts varied by hybrid, SF, and seeding rate (data not shown). Seeds remained in the soil for approximately 29 to 42 days prior to emergence.

Plant spacing standard deviation was affected by hybrids and populations (data not shown). Late season stand counts varied by hybrid in 2012 (Data not shown).

Starter fertilizer increased estimated individual plant biomass by 18% in 2011 at the V3 sampling but had no affect at V9 or R2 (Table 8). Estimated plant biomass increased with SF by 27, 20, and 6% at the V3, V9, and R2 samplings respectively in 2012 (Table 8). In 2012, increasing seeding rate above 74.1×10^3 seeds·ha^{-1} reduced plant biomass at V9 and R2 (Table 8). In both years, increasing seeding rates resulted in smaller estimated plant biomass at the R2 sampling (Table 8). Hybrid 3 had larger estimated plant biomass than hybrids 1 and 2 at R2 in 2011 (Table 8).

In 2012, SF increased average developmental stage of plants by 0.1 stages at the V3 sampling and by 0.4 stages at the V9 sampling (Table 9). Increasing seeding rate from 74.1×10^3 seeds·ha^{-1} to 103.7×10^3 seeds·ha^{-1} resulted in a reduction in developmental stage by 0.3 stages at the V9 sampling in 2012 (Table 9). In 2011, hybrid 2 was more developed (0.1 developmental stage) than hybrids 1 and 3 at the V3 sampling (Table 9). However, at the V9 sampling, hybrids were all different with stages in the order of most developed to least hybrid 2, 1, and 3, respectively in 2011 (Table 9). Hybrid 3 was less developed than hybrids 1 and 2 at both samplings in 2012 (Table 9).

Starter fertilizer increased kernel rows plant^{-1} by 0.6 and kernel number plant^{-1} by 49 in 2012 but SF affected neither of these variables in 2011 (Table 10). Many plants aborted kernel rows, resulting in ears commonly referred to as zipper ears in 2012, however, SF had no effect on the amount of plants with aborted rows (P = 0.7387, data not shown). Starter fertilizer increased yield plant^{-1} by 8.2 g in 2011 and 14.4 g in 2012 (Table 10). Grain moisture plant^{-1} at hand harvest was 0.9 g·kg^{-1} lower with SF in 2012 (Table 10). Starter fertilizer increased yield ha^{-1} by 0.89 Mg·ha^{-1} in 2012, however, not in 2011 (Table 10). Starter fertilizer increased grain yield at the 74.1 × 10^{3} and 88.9 × 10^{3} seeds·ha^{-1} by 1.17 Mg·ha^{-1} and 1.58 Mg·ha^{-1}, respectively, but not at the 103.7 × 10^{3} seeds·ha^{-1} rate at Nashua (data not shown). Grain moisture at combine harvest was reduced with SF by 0.1 g·kg^{-1} in 2011 and 0.2 g·kg^{-1} in 2012 (Table 10).

Increasing seeding rate above 74.1 × 10^{3} seeds·ha^{-1} resulted in fewer kernel rows ear^{-1} in 2012 (Table 10) and fewer kernels plant^{-1} and less grain yield plant^{-1} in both years (Table 10). Plant moisture^{-1} increased with each increase in seeding rate in 2011, however in 2012, the seeding rate of 103.7 × 10^{3} seeds·ha^{-1} had higher moisture plant^{-1} than the seeding rate of 74.1 × 10^{3} seeds·ha^{-1} (Table 10). In 2011, the seeding rates of 88.9 × 10^{3} and 103.7 × 10^{3} seeds·ha^{-1} yielded more grain ha^{-1} than 74.1 × 10^{3} seeds·ha^{-1}, while in 2012 the seeding rate of 74.1 × 10^{3} seeds·ha^{-1} yielded more than the seeding rate of 103.7 × 10^{3} seeds·ha^{-1} (Table 10). Increasing seeding rate above 88.9 × 10^{3} seeds·ha^{-1} resulted in higher grain moisture at harvest in 2011, however, in 2012 increasing seeding rate above 74.1 × 10^{3} seeds·ha^{-1} resulted in higher grain moisture at harvest (Table 10).

Kernel rows ear^{-1} varied by hybrid in both years; hybrids are ordered from most to least kernel rows: hybrid 2, 3, and 1 in 2011 (Table 10). Hybrid 2 produced less kernel rows ear^{-1} than hybrids 1 and 3 in 2012 (Table 10). Kernel number plant^{-1} and grain yield plant^{-1} varied with hybrid and are ordered from the most to least: hybrid 3, 1, and 2 in 2011 (Table 10). Hybrids 1 and 2 produced fewer kernels plant^{-1} and less yield plant^{-1} than hybrid 3 in 2012 (Table 10). Grain moisture plant^{-1} was different for hybrids and increased in the order of hybrid 3, 1, and 2 in 2011 (Table 10). In 2012, hybrid 1 had drier grain moisture plant^{-1} at hand harvest than hybrids 2 and 3 (Table 10). Hybrids ranked in order from the least yield to the most ha^{-1} in 2011: hybrid 3, 1, and 2 (Table 10). Hybrids did not yield differently in 2012. Grain moisture at combine harvest was more for hybrids 1 and 3 compared to hybrid 2 in 2011; however, hybrid 3 had higher grain moisture than hybrids 1 and 2 in 2012 (Table 10).

Discussion

Starter fertilizer did not affect emergence date but increased early-season growth of corn in both years and at both locations similar to results of other researchers (Bermudez and Mallarino, 2002; Bullock et al., 1993). Starter fertilizer increased growth from V2 – V15 at Ames and V3-R2 at Nashua, similar to the results of Bullock et al., (1993) who found SF increased plant size at 400-500 GDDs after planting and the increase in growth remained until 1200 GDDs after planting. Hybrids did not respond differently to SF application similar to the results of Buah et al., (1999), however, our findings contrast with the results of authors who found differential hybrid response to SF Gordon and Pierzynski, (2006) and Rhoads and Wright, (1998). In our study, hybrids differed in development in both years, and the hybrid with shorter relative maturity reached anthesis earlier. Late season stand reduction with SF at Ames in 2011 may have been a result of increased competitive ability of early emerging plants, leading to higher mortality of late emerging plants (Pierson et al., 2013). The hybrid and seeding rate interaction for plant spacing standard deviation that occurred in 2011 could be related to seed size and shape and the planter type used. DuPont Pioneer developed a tool to estimate plant ability of their hybrids with different planter types (DuPont Pioneer, 2013) but the seed lot of the hybrid in question was not available on the calculator.

Even though emergence was not affected by SF, development was hastened with SF application at 8 of 9 sampling dates at Ames and at 3 of 4 sampling dates at Nashua. Starter fertilizer reduced days from planting to silking at Ames both years. Grain moisture plant^{-1} after maturity was lower with SF in all site years and combine harvest grain moisture decreased with SF applied at all site years except Ames 2011. These results agree with Bullock et al., (1993) in showing that SF application increases developmental rate of corn. Altered developmental rate of corn may result in different environmental conditions during critical pollination and grain fill periods resulting in yield differences. Starter fertilizer increased ASI in 2011, however the opposite occurred in 2012; environmental stress during the time bracketing silking has been shown to negatively affect yield (Westgate et al., 1997) and the SF may affect corn response to the environment. In 2012, fertility and drought during pollination and grain fill were concerns and reducing stress with SF potentially increased yield. Hybrids and seeding rates differed in their days from emergence to silking. Increasing seeding rates generally reduced plant size, resulted in slower development, and increased days from emergence to silking. Increasing seeding rates reduced ASI in 2011, however, increasing seeding rates in 2012 increased ASI; the latter is similar to results of (Boomsma et al., 2009). Our average measured ASI was similar in comparison to reported results (Boomsma et al., 2009). Year differences in ASI response to starter fertilizer and seeding rates were likely related to lack of fertility and drought enhanced stress in 2012. Furthermore, hybrid and seeding rate interactions occurred for ASI in which hybrids responded to increasing seeding rates differently. Breeders have been selecting for hybrids that have reduced ASI and are modern hybrids are more tolerant to stress which includes increased planting density (Bolanos and Edmeades, 1993; Bolanos and Edmeades, 1996; Tollenaar and Wu, 1999).

Kernel rows ear^{-1} increased in 2012 with SF applied suggesting that SF reduced plant stress at or prior to V7, which is approximately when kernel rows ear^{-1} is determined (Stevens et al., 1986; Abendroth et al., 2011); however, many of the ears both with and without SF had partially or fully aborted kernel rows which would have occurred post anthesis but before R3 (Abendroth et al. 2011). Starter fertilizer had no effect on the number of plants with partially or fully aborted kernel rows. Grain yield plant^{-1} increased with SF at Nashua in 2011; however, this response is possibly due to non-uniform and poor emergence of corn in 2011 due to extended days from planting to emergence. Kernel number plant^{-1} and grain yield plant^{-1} also increased with SF in 2012. Starter fertilizer had no effect on grain yield ha^{-1} in 2011, conversely, SF increased grain yield ha^{-1} in 2012 at both locations. Soil test results for P were optimum to high in 2011, however, low to very low in 2012. Our yield results in 2011 tend to agree with the results of (Bermudez and Mallarino, 2004; Bullock et al., 1993; Kaiser et al., 2005) in that SF application did not increase yield. Our results were also similar to those who found that phosphorus SF in addition to broadcast fertilizer -to raise soil test levels to optimum - did not increase yield (Kaiser et al., 2005; Mallarino et al., 2011). Yield response to SF in 2012 was likely related to low soil fertility that was remediated by application of SF. Yield results of 2012 tend to agree with those of Bermudez and Mallarino, (2002) and Buah et al., (1999) where SF increased grain yield but contrary to Gordon et al.,(1997), Gordon and Pierzynski, (2006), and Teare and Wright, (1990), since hybrids did not respond differentially to SF. The studies that found hybrid responses to SF application occurred in different geographic areas, i.e. Kansas, and Florida that have different soils and meteorological patterns than Iowa. Also, hybrids are bred for different environments; hybrids bred for the northern Midwest may have rooting differences compared to those bred for warmer regions. In 2011, seeding rates were not affected by SF application at either location. However, SF increased grain yield at the 74.1 and 88.9 × 10^3 seeds·ha^{-1} but not at the 103.7 × 10^3 seeds·ha^{-1} rate at Nashua which was likely due to moisture being a limiting factor at the higher seeding rate. Yield responses reported by others to SF have been variable, however, recommendations to use SF have been made based on either low soil test levels, in situations with limited soil moisture , or if fertilizer efficiency is to be maximized (Randall and Hoeft, 1988).

Conclusion

Starter fertilizer may hasten corn development if timely planting is not possible. The ability to apply fertilizer in a band near the seed could be used as a risk management tool for farmers concerned about nutrient availability and reducing the probability of frost prior to crop maturity. Starter fertilizer increased yield of the low and medium seeding rates, but did not increase yield at the high seeding rate in 2012 at Nashua, IA. This was probably due to the moisture stress during the drought at the high seeding rate. Hybrids and seeding rates were not affected by SF in other parameters measured, suggesting that SF affects hybrids and seeding rates equally. Furthermore, we did not find that root strength ratings of hybrids were indicative of hybrid response to SF. Starter fertilizer did alter time from planting to silking and anthesis; altering the timing of this critical period may result in environmental conditions more or less conducive to grain fill. Also, variability of soil fertility in a field may be another reason why some find SF responses while others do not. Our plots in 2012 at Nashua were directly north of the plots from 2011 and the research areas were similar in management, however, rotated between corn and soybeans. Our soil test results in 2011 were optimum to high while in 2012 they were low to very low. Differences in soil tests within large fields may explain responses to SF applications. Although SF application equipment is expensive, fields with extreme variation in nutrients may benefit from SF.

Table 1. Accumulated Growing Degree Days (GDDs) after seeding for each sampling stage at Ames, IA and Nashua, IA in 2011 and 2012. Growing Degree Days were calculated using information compiled from Iowa Environmental Mesonet; GDDs were calculated in °C.

		GDDs after seeding	
Ames	Sampling stage	2011	2012
	V2	123	153
	V4	250	221
	V6	340	290
	V9	477	498
	V15	670	685
	R2	824	933
Nashua	V3	140	286
	V8	426	605
	R2	844	1053

Table 2. Parameters for biomass equations at each development stage during 2011 and 2012 at both locations. Equations were developed using SAS PROC REG correlating plant height and stem diameter to measured plant biomass.

	Development stage	Intercept	Height	Stem diameter	Stem diameter^2	R^2
Ames						
2011	V2	-0.08178	0.01142	0.03248	-0.00392	0.57
	V4	0.03097	0.04032	-0.21899	0.02036	0.79
	V6	-0.44809	0.10744	-0.47866	0.02317	0.83
	V9	-9.85963	0.31422	-1.83359	0.07502	0.85
	V15	-8.58485	0.79943	-13.05423	0.43768	0.73
	R2	-97.66933	0.36275	2.76720	0.15903	0.78
2012	V2	-0.06890	0.02365	-0.06910	0.01239	0.80
	V4	-0.34018	0.04848	-0.12082	0.01351	0.91
	V6	0.21454	0.09130	-0.53933	0.03218	0.95
	V9	5.86665	0.78563	-3.60982	0.12962	0.94
	V15	6.97339	2.19451	-14.75962	0.49362	0.84
	R2	-53.36158	1.83900	-9.5239	0.53527	0.89
Nashua						
2011	V3	0.00278	0.01406	-0.06086	0.01084	0.91
	V9	-8.83925	0.96366	-1.70788	0.05394	0.79
	R2	-81.55136	1.20335	-1.17941	0.24236	0.70
2012	V3	-0.21651	0.03116	-0.04909	0.00964	0.86
	V9	-5.57619	0.98030	-3.04556	0.11363	0.91
	R2	-127.02261	0.50032	8.35711	0.15290	0.73

Table 3. Starter fertilizer, seeding rate, and hybrid effects on average days to emergence after planting and average estimated biomass at different biomass sampling times at Ames, IA. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}. Biomass was estimated using models developed through destructive sampling of 360 plants per sampling date utilizing height and stem diameter measurements that were then correlated to biomass (see Table 2 for model variables).

			Estimated biomass (g·plant^{-1})					
			Developmental stage					
Year	Starter	Emergence (days)	V2	V4	V6	V9	V15	R2
2011	Yes	8.42 a‡	0.09 a	0.92 a	4.0 a	26 a	86 a	109 a
	No	8.41 a	0.09 a	0.73 b	3.3 b	23 b	84 a	113 a
2012	Yes	9.16 a	0.30 a	1.01 a	2.6 a	26 a	89 a	126 a
	No	9.19 a	0.26 b	0.82 b	2.1 b	22 b	77 b	118 a
	Seeding rate (Seeds·ha^{-1})							
2011	74,1 × 10^3	8.45 a	0.09 a	0.87 a	3.8 a	27 a	96 a	126 a
	88.9 × 10^3	8.39 a	0.09 a	0.80 b	3.6 b	24 b	84 b	107 b
	103.7 × 10^3	8.40 a	0.09 a	0.81 b	3.6 b	23 c	75 c	98 c
2012	74.1 × 10^3	9.22 a	0.28 a	0.93 a	2.5 a	28 a	99 a	146 a
	88.9 × 10^3	9.14 a	0.27 a	0.90 a	2.3 b	23 b	80 b	118 b
	103.7 × 10^3	9.19 a	0.28 a	0.93 a	2.4 ab	22 b	71 c	101 c
	Hybrid							
2011	1†	8.31 a	0.10 a	0.86 a	3.9 a	25 a	85 a	108 a
	2	8.58 b	0.08 b	0.76 b	3.3 b	24 b	86 a	114 a
	3	8.36 a	0.10 a	0.86 a	3.8 a	24 b	84 a	109 a
2012	1	9.17 a	0.30 a	1.01 a	2.6 a	25 a	81 a	119 a
	2	9.10 a	0.27 b	0.88 b	2.3 b	23 b	84 a	123 a
	3	9.25 b	0.26 b	0.87 b	2.2 b	24 ab	84 a	123 a

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.
‡ Means within the same column and the same year followed by the same letter are not different ($P \leq 0.05$).

Table 4. Starter fertilizer, seeding rate, and hybrid effects on corn vegetative developmental stage measured by a modified Iowa State University method (Abendroth et al, 2011) with which plants were staged to 0.25 accuracy. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}. Values were recorded at stages reported as growing degree days after seeding in both 2011 and 2012. There were 720 plants sampled per developmental stage at Ames, IA.

Treatment		Starter fertilizer		Seeding rate (seeds ha^{-1})			Hybrid		
		Average developmental stage							
Year	Developmental Stage	Yes	No	74.1×10^3	88.9×10^3	103.7×10^3	1†	2	3
2011	V4‡	4.46 a§	4.31 b	4.42 a	4.35 b	4.37 b	4.44 a	4.39 b	4.31 c
	V6	6.33 a	6.20 b	6.33 a	6.23 b	6.23 b	6.31 a	6.26 ab	6.22 b
	V9	9.00 a	8.77 b	9.02 a	8.82 b	8.80 b	8.99 a	8.99 a	8.68 b
	V15	15.58 a	15.21 b	15.77 a	15.27 b	15.14 b	15.24 a	15.42 b	15.52 b
2012	V2	2.32 a	2.52 a	2.27 a	2.25 a	2.73 a	2.32 a	2.27 a	2.67 a
	V4	4.02 a	3.81 b	3.95 a	3.89 a	3.91 a	4.02 a	3.96 a	3.76 b
	V6	5.41 a	5.30 b	5.41 a	5.33 b	5.32 b	5.40 a	5.38 a	5.28 b
	V9	8.92 a	8.66 b	8.94 a	8.73 b	8.71 b	8.90 a	8.89 a	8.58 b
	V15	14.84 a	14.01 b	14.82 a	14.32 b	14.13 b	14.43 a	14.41 a	14.44 a

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.

‡ Vegetative growth stage was not recorded at V2 sampling in 2011.

§ Means within the same row and the same year within the same treatment such as starter fertilizer, seeding rate, and hybrid followed by the same letter are not different ($P \leq 0.05$).

Table 5. Hybrid, starter fertilizer, and seeding rate effects on silking, anthesis, and anthesis-silking interval (ASI) at Ames, IA. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 $kg \cdot ha^{-1}$.

	Starter	Seeding rate	Hybrid	Silking	Anthesis	ASI
2011	Yes			74.2 a‡	74.7 a	0.4 b‡
	No			75.1 b	75.2 b	0.1 a
		74.1×10^3		74.0 a	74.6 a	0.6 c
		88.9×10^3		74.8 b	75.0 b	0.2 b
		103.7×10^3		75.3 c	75.3 c	-0.1 a
			1†	74.8 b	75.3 b	0.5 b
			2	75.4 c	75.4 b	-0.1 a
			3	73.9 a	74.2 a	0.3 b
2012	Yes			70.8 a	71.6 a	1.0 b
	No			71.9 b	73.1 b	1.3 a
		74.1×10^3		71.1a	71.6 a	0.7 a
		88.9×10^3		71.4 b	72.3 b	1.1 b
		103.7×10^3		71.5 b	73.0 c	1.5 c
			1	71.4 b	72.1 b	0.7 a
			2	72.3 c	73.7 c	1.6 c
			3	70.3 a	71.2 a	1.0 b

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.

‡ Means within the same starter fertilizer, seeding rate or hybrid and the same year followed by the same letter are not different ($P \leq 0.05$).

‡ ASI values were calculated $plant^{-1}$ and differences between the ASI value and the difference between silking and anthesis values are due to missing values for silking or anthesis.

Table 6. Hybrid and seeding rate interaction for anthesis-silking interval (ASI) duration at Ames, IA in 2011 and 2012. Silking was determined as the date of the first green silk emerging from the husk and anthesis was determined as the date of the first pollen anther open on the tassel. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 $kg \cdot ha^{-1}$.

		ASI	
Hybrid	Seeding rate	2011	2012
1†	74.1×10^3	0.6 ab‡	0.5 d
	88.9×10^3	0.4 b	0.9 bcd
	103.7×10^3	0.3 b	0.8 cd
2	74.1×10^3	0.5 ab	1.1 bcd
	88.9×10^3	-0.2 c	1.3 bc
	103.7×10^3	-0.4 c	2.4 a
3	74.1×10^3	0.8 a	0.6 d
	88.9×10^3	0.4 b	1.1 bcd
	103.7×10^3	-0.3 c	1.4 b
P Value		0.0136	0.0502

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.

‡ Means within the same column and the same year followed by the same letter are not different ($P \leq 0.05$).

Table 7. Hybrid, starter fertilizer, and seeding rate effects on grain yield components of hand harvested ears including plant^{-1} ear row number, kernel number, yield, and moisture at Ames, IA. Grain yield ha^{-1} and harvest moisture are included. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}.

Year	Starter	Seeding Rate	Hybrid	Row number plant^{-1}	Kernel Number plant^{-1}	Yield (g plant^{-1})	Grain moisture plant^{-1} (g·kg^{-1})	Combine Yield (Mg·ha^{-1})	Combine Harvest moisture (g·kg^{-1})
2011	Yes			15.4 a‡	475 a	133.6 a	22.3 a	13.71 a	15.3 a
	No			15.6 a	472 a	133.2 a	23.5 b	13.78 a	15.4 a
		74.1×10^3		15.8 a	537 a	157.1 a	22.2 a	13.45 b	15.4 a
		88.9×10^3		15.8 a	476 b	133.2 b	23.2 b	13.65 b	15.4 a
		103.7×10^3		15.0 b	408 c	111.5 c	23.3 b	14.13 a	15.4 a
			1†	15.2 b	462 a	134.0 a	23.2 a	14.05 a	15.5 b
			2	16.4 a	474 a	130.9 a	23.1 a	13.64 ab	15.1 a
			3	15.0 b	485 a	136.9 a	22.4 a	13.54 b	15.5 b
2012	Yes			12.5 a	306 a	78.8 a	17.6 a	7.70 a	17.7 a
	No			11.4 b	263 b	66.6 b	19.1 b	6.91 b	18.2 b
		74.1×10^3		13.4 a	363 a	95.3 a	17.8 a	7.93 a	17.6 a
		88.9×10^3		11.7 b	269 b	68.8 b	18.0 a	7.55 a	17.9 ab
		103.7×10^3		10.7 b	226 c	54.1 c	19.3 a	6.46 b	18.2 b
			1	12.5 a	280 b	74.1 a	16.7 a	7.44 a	17.4 a
			2	10.1 b	235 c	62.2 b	21.4 b	6.32 b	18.3 b
			3	13.2 a	343 a	81.7 a	17.0 a	8.17 a	18.0 b

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.
‡ Means within the same column and the same year and same variable followed by the same letter are not different ($P \leq 0.05$).

Table 8. Starter fertilizer, seeding rate, and hybrid effects on average estimated biomass across biomass samplings at Nashua, IA. Starter fertilizer was 11-52-0 (monoammonium phosphate) applied at a rate of 112.1 kg·ha^{-1}. Biomass was estimated using models developed through destructive sampling of 360 plants per sampling date utilizing height and stem diameter measurements that were then correlated to biomass.

		Estimated biomass (g·plant^{-1})		
		Developmental stage		
Year	Starter Fertilizer	V3	V9	R2
2011	Yes	0.26 a‡	27 a	159 a
	No	0.22 b	24 a	156 a
2012	Yes	0.52 a	36 a	166 a
	No	0.41 b	30 b	156 b
	Seeding rate			
2011	74.1×10^3	0.24 a	26 a	172 a
	88.9×10^3	0.23 a	25 a	157 b
	103.7×10^3	0.25 a	26 a	143 c
2012	74.1×10^3	0.48 a	36 a	182 a
	88.9×10^3	0.45 a	32 b	155 b
	103.7×10^3	0.47 a	31 b	145 c
	Hybrid			
2011	1†	0.24 a	25 a	150 b
	2	0.26 a	25 a	154 b
	3	0.22 a	26 a	169 a
2012	1	0.48 a	34 a	157 a
	2	0.47 a	32 a	162 a
	3	0.45 a	33 a	164 a

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.

‡ Means within the same row and the same year followed by the same letter are not different ($P \leq 0.05$).

Table 9. Starter fertilizer, seeding rate, and hybrid effects on corn vegetative developmental stage measured by a modified Iowa State University method (Abendroth et al, 2011) with which plants were staged to 0.25 accuracy. Values were recorded at stages reported as growing degree days after seeding in both 2011 and 2012. There were 720 plants sampled per developmental stage at Nashua, IA. Starter fertilizer was 11-52-0 (monoammonium phosphate) applied at a rate of 112.1 $kg \cdot ha^{-1}$.

Treatment		Starter fertilizer		Seeding rate (seeds ha^{-1})			Hybrid		
		Average developmental stage							
Year	Development stage	Yes	No	74.1×10^3	88.9×10^3	103.7×10^3	1†	2	3
2011	V3	3.04 a‡	2.96 a	2.98 a	3.01 a	3.01 a	2.97 b	3.09 a	2.95 b
	V9	8.36 a	8.21 a	8.35 a	8.26 a	8.25 a	8.31 b	8.54 a	8.01 c
2012	V3	3.32 a	3.18 b	3.24 a	3.24 a	3.26 a	3.25 a	3.27 a	3.22 b
	V9	9.33 a	8.94 b	9.28 a	9.10 ab	9.02 b	9.25 a	9.25 a	8.89 b

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.

‡ Means within the same starter fertilizer, seeding rate and hybrid and the same year followed by the same letter are not different ($P \leq 0.05$).

Table 10. Nashua hybrid, starter fertilizer, and seeding rate effect on grain yield components of hand harvested ears including $plant^{-1}$ ear row number, kernel number, yield, and moisture. Grain yield ha^{-1} and harvest moisture are included. Starter fertilizer was 11-52-0 (monoammonium phosphate) applied at a rate of 112.1 $kg\cdot ha^{-1}$.

	Starter Fertilizer	Seeding Rate	Hybrid	Row number $plant^{-1}$	Kernel number $plant^{-1}$	Yield (g $plant^{-1}$)	Grain moisture $plant^{-1}$ ($g\cdot kg^{-1}$)	Combine yield ($Mg\cdot ha^{-1}$)	Combine harvest moisture ($g\cdot kg^{-1}$)
2011	Yes			16.2 a‡	555 a	175.9 a	23.7 a	12.54 a	19.0 a
	No			16.3 a	535 a	167.2 b	24.2 a	12.56 a	19.1 b
		74.1×10^3		16.4 a	580 a	190.3 a	22.8 a	12.03 b	18.9 a
		88.9×10^3		16.2 a	550 b	170.9 b	24.0 b	12.71 a	19.0 a
		103.7×10^3		16.1 a	505 c	153.4 c	24.9 c	12.91 a	19.2 b
			1†	15.8 c	544 b	172.9 b	23.6 b	12.60 b	19.1 b
			2	16.9 a	513 c	157.1 c	25.4 c	13.18 a	18.7 a
			3	16.1 b	577 a	184.6 a	22.7 a	11.87 c	19.2 b
2012	Yes			15.2 a	413 a	120.2 a	15.2 a	9.88 a	15.1 a
	No			14.6 b	364 b	105.8 b	16.1 b	8.99 b	15.3 b
		74.1×10^3		15.4 a	454 a	134.4 a	15.2 a	9.77 a	15.0 a
		88.9×10^3		14.7 b	377 b	108.9 b	15.8 ab	9.52 ab	15.2 b
		103.7×10^3		14.5 b	334 c	95.7 c	16.1 b	9.01 b	15.3 b
			1	15.1 a	369 a	109.1 b	14.5 a	9.41 a	14.8 a
			2	14.2 b	369 a	110.0 b	16.6 b	9.15 a	14.9 a
			3	15.3 a	427 b	119.9 a	16.0 b	9.74 a	15.7 b

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.
‡ Means within the same row and the same year followed by the same letter are not different ($P \leq 0.05$).

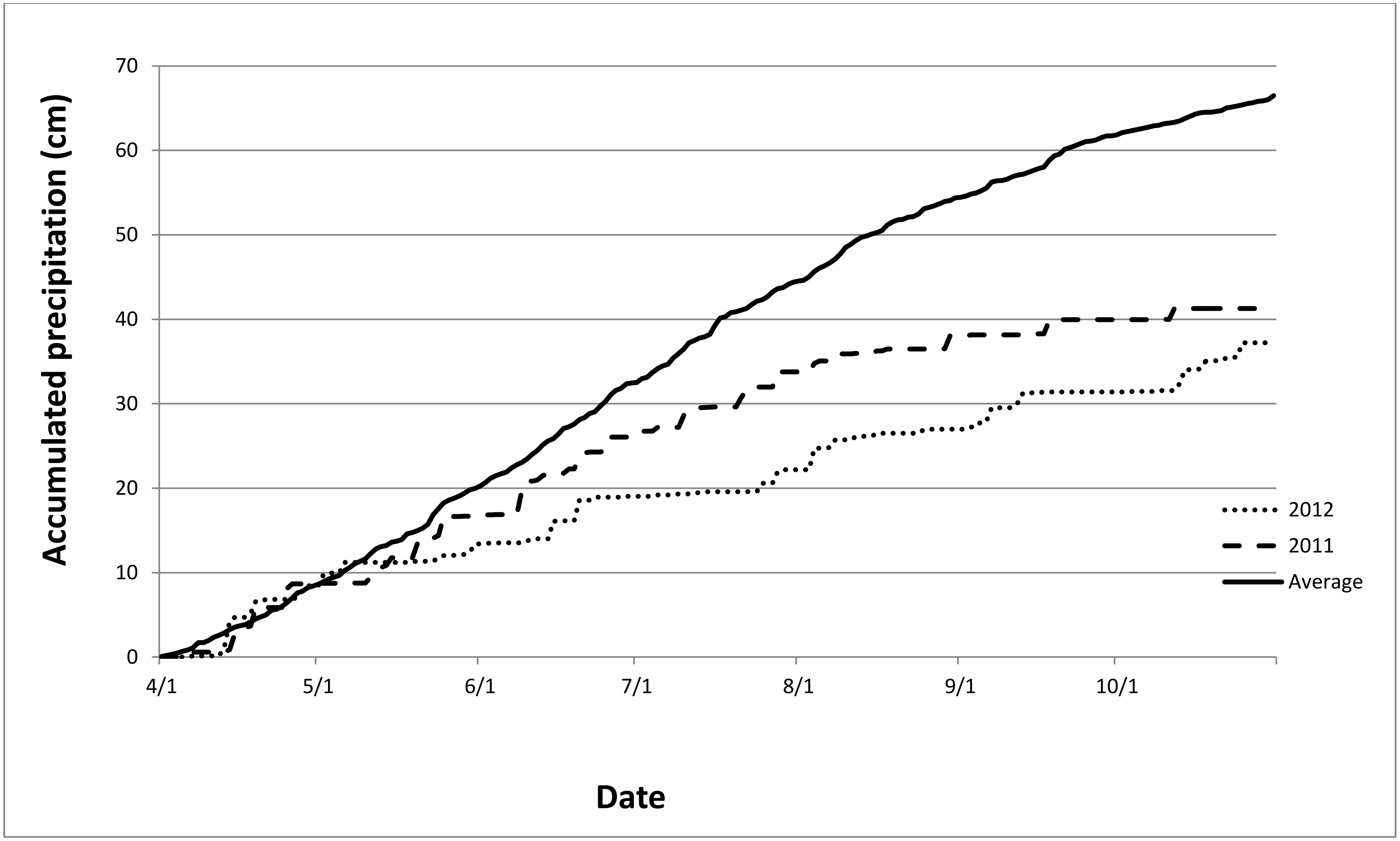

Figure 1. Accumulated precipitation for the growing seasons of 2011, 2012, and the 26 - year average. Ames, IA.

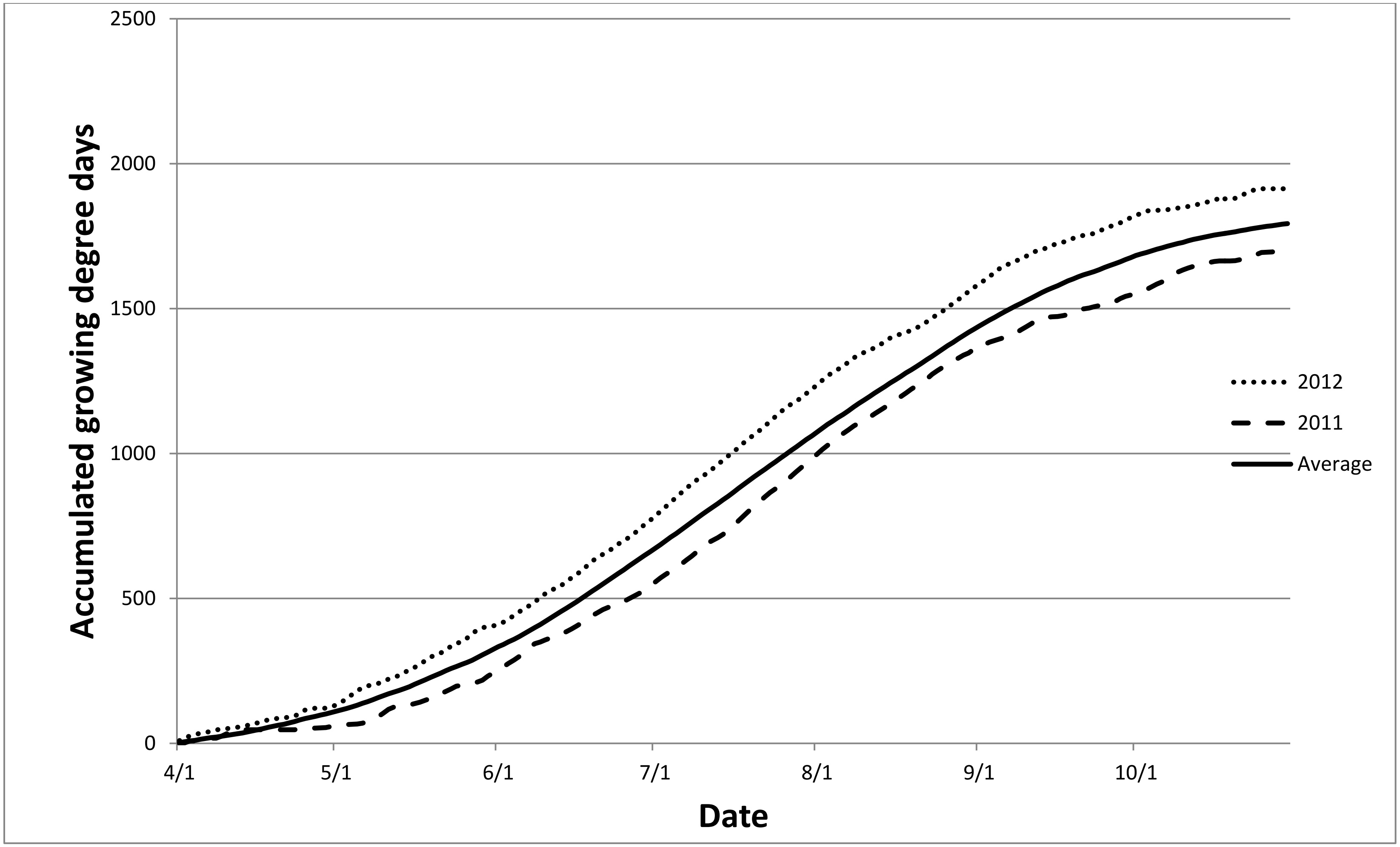

Figure 2. Accumulated growing degree days (°C) for the growing seasons of 2011, 2012, and the 26 - year average. Ames, IA.

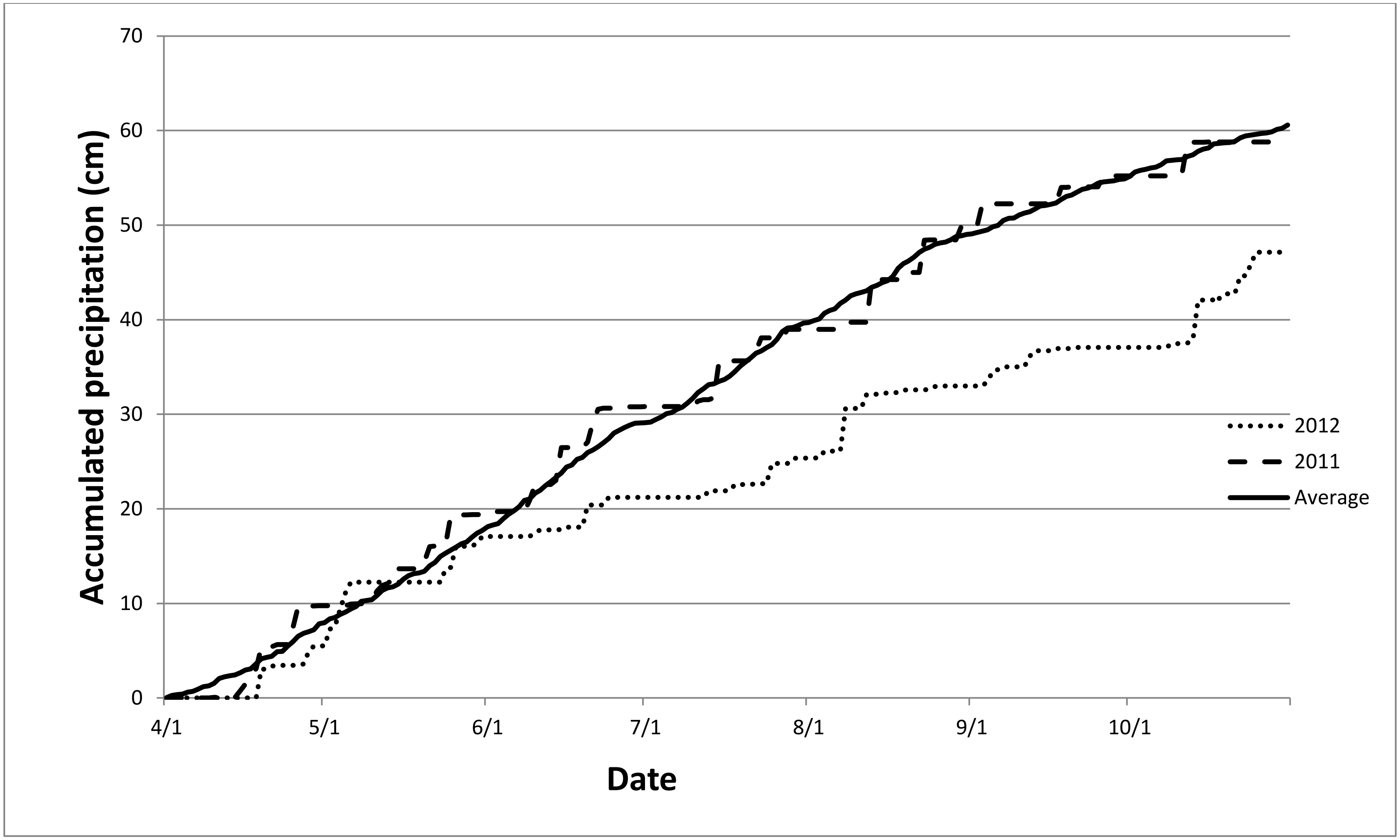

Figure 3. Accumulated precipitation for the growing seasons of 2011, 2012, and the 24 - year average. Nashua, IA.

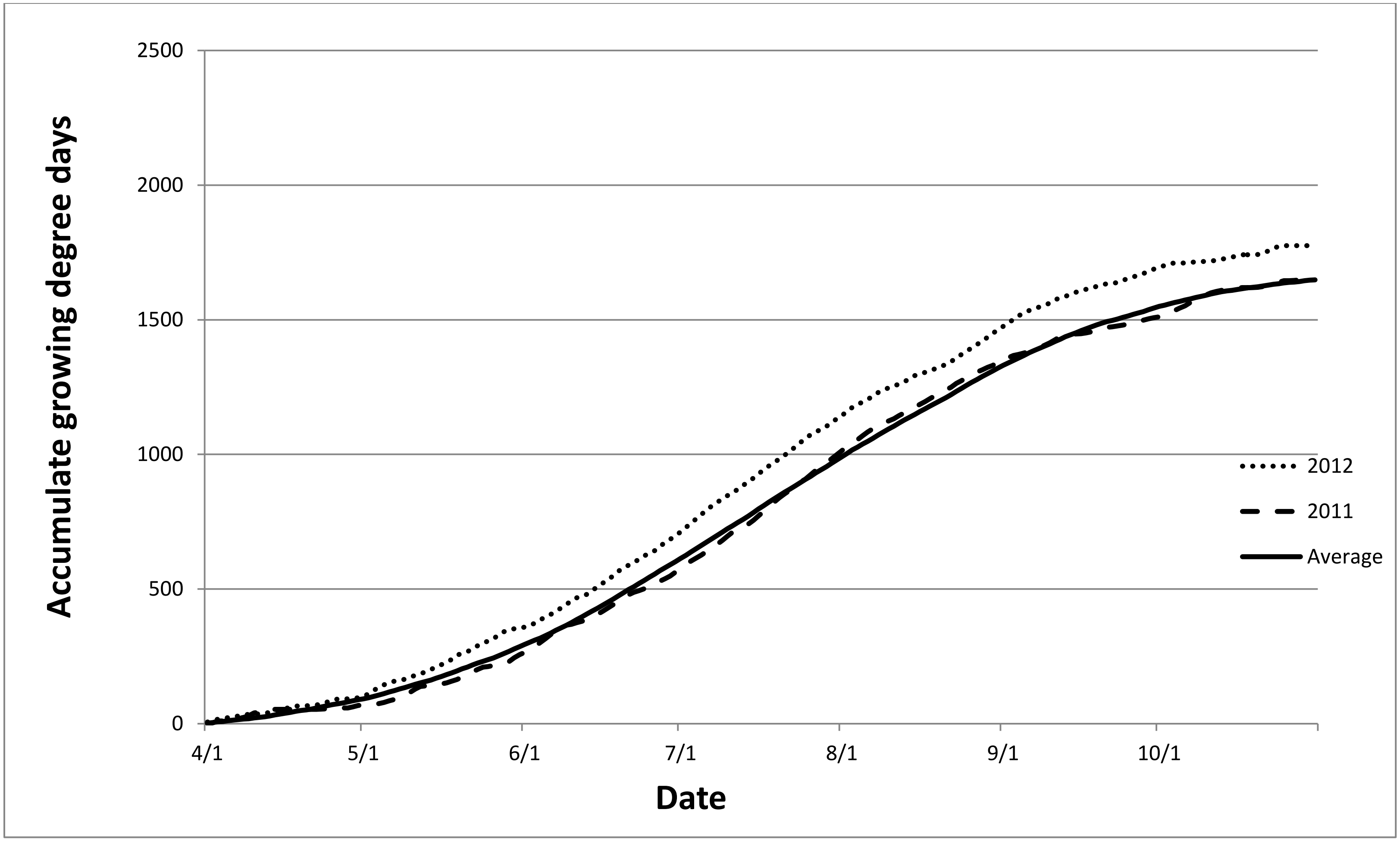

Figure 4. Accumulated growing degree days (°C) for the growing seasons of 2011, 2012, and the 24 - year average. Nashua, IA.

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CHAPTER 3: ROOT GROWTH IN RELATION TO CORN HYBRID, SEEDING RATE, AND STARTER FERTILIZER

A paper in preparation for *Agronomy Journal*

Abstract

Corn (*Zea mays* L.) root growth research has focused on characteristics such as root length, radius, surface area, and root biomass to understand nutrient uptake. Nutrient uptake generally increases with increased root surface areas. Corn hybrids, seeding rates, and starter fertilizer (SF) treatments affect corn root growth. Our objective was to determine whether hybrids and seeding rates responded to SF differently. If hybrids or seeding rates responded to SF differently, we wanted to determine whether differences in root systems reflected the response to SF. We destructively sampled plants for root and shoot biomass at Ames, IA in 2011 and 2012 at approximately V2 and V4. Plant roots were washed, scanned, analyzed by a scanner-based root analysis program, dried, and weighed for biomass. The program analyzed roots for root characteristics including root length, diameter, surface area, number of tips, and number of forks. We also measured shoot parameters such as height, stem diameter, and shoot biomass. Hybrids with smaller root systems without SF responded to SF in terms of shoot and root biomass. A hybrid that had a root system similar to the root system of those that responded to SF with SF did not respond to SF in shoot and root biomass. Also, seeding rates responded to SF differently in that the low seeding rate responded to SF sooner than the medium and high seeding rates. Differential root growth with hybrids and seeding rates may explain variable yield response to SF applications in Iowa. Agronomists and farmers should consider the impacts of management decisions on

crop shoot and root growth and development to have a better understanding of yield responses.

Introduction

Roots are the main pathway for nutrient and water uptake of a plant, however, research on root growth is limited due to difficulty in sampling compared to shoot growth. Even with the work that is done, researchers often focus on the fine root system because of its impact on water and nutrient uptake (Barber, 1976; Eissenstat, 1992). Root characteristics often studied are root length, radius, surface area, and root biomass (Barber and Silberbush, 1984; Richner et al., 1996; Smika and Klute, 1982). These characteristics influence root nutrient uptake; nutrient uptake rate generally increases with increased root surface area (Barber and Silberbush, 1984).

Corn root growth studies began with methods such as growing corn in pots and excavating roots (Weihing, 1935) or removing slabs of soil from fields and washing roots from the slab for measurement (Foth, 1962). Soil cores of various diameters and depths have often been used to describe root length density; in these studies, root volume is compared to the volume of soil removed (Barber, 1971; Onderdonk and Ketcheson, 1973; Qin, Stamp, et al., 2005). These soil cores are generally taken within rows of corn as well as at varying distances from corn rows; soil cores are then washed and roots measured using microscopes or computer analyses using photos or scanned images of root systems and root analysis programs (Fehrenbacher and Alexander, 1955; Onderdonk and Ketcheson, 1973; Qin, Stamp, et al., 2005). Minirhizotrons have also been used to measure root growth during a growing season; a minirhizotron is a tube inserted into the soil toward a plant row at an angle; a digital camera, connected to a monitor and recording images, is inserted into the tube and images of roots recorded (Nickel et al., 1995). Whole root biomass has also been sampled from plants grown in greenhouses in pots (Costa et al., 2000; Rhoads and Wright, 1998). Plants were removed from pots, soil washed from the roots, roots cut into approximately 10 mm lengths, stained, and then placed into a mixing device; the resulting sample was then subsampled. Subsamples were then placed on a translucent Plexiglass tray for image acquisition with an electronic computer-based scanner. The images were analyzed with the scanner-based software program winRHIZO (Regent Instruments, Quebec City, Quebec, Canada).

Soil temperature, moisture, compaction, and light availability affect root growth. Increasing air temperature from 18 °C to 25 °C while soil temperature remained at 18 °C increased root growth 2.7 times and P uptake 2.2 times (Mackay and Barber, 1984). Stover placed on soil surface decreased maximum daily soil temperature 2.5 °C at 10 cm depth and also resulted in more roots in the upper 5 cm of soil (Onderdonk and Ketcheson, 1973). Other researchers found that 2- 3 °C reductions in soil temperatures may adversely affect growth of chilling-sensitive maize seedlings in the field (Richner et al., 1996). Annual differences in root and shoot growth, and development rate were attributed to differences in soil and air temperatures related to planting date differences (Mengel and Barber, 1974). Corn roots and shoots grew and developed more rapidly with warmer temperatures due to a late planting date in 1970 compared to an early planting date and cooler soil temperatures in 1971 (Mengel and Barber, 1974). Although soil temperature had the most dramatic effect on root elongation, other factors such as bulk density, oxygen stress, and moisture stress all affected root growth (Logsdon et al., 1987). Other scientists found that root length density decreased by one-third due to compaction in trafficked rows (Kaspar et al., 1995). Shading of corn plants to imitate shading at different seeding densities indicated that biomass allocation to roots varied with plant genetics (Hebert et al., 2001). Generally, increasing seeding density results in more biomass allocation to the shoot and less to the root. Corn grown in rotation with soybean had greater root length density, measured at 0-100 cm depth, than continuous corn except in the top 12.5 cm of the soil where continuous corn had 22% greater root length density at approximately V5 (Nickel et al., 1995).

Nutrients and their placement also affect root growth. Broadcast nitrogen (N) fertilization decreased root diameter while increasing root length – without changing root weight – in 2 of 3 years (Anderson, 1987). Corn root length also increased with increasing plant size and increasing N rates and different N timings (Bonifas and Lindquist, 2009; Durieux et al., 1994). Research on N rates performed in a greenhouse showed that a rate of 127.5 kg N ha^{-1} compared to 0 and 255 kg N ha^{-1} resulted in greater root length and surface area at silking (Costa et al., 2002). Starter fertilizer increased root-length density and diameter one of two years at two locations and was effective in the buildup of the root system at anthesis (Qin et al., 2005). The year with a response of increased root-length density and diameter had especially cool temperatures for corn growth compared to the year without response to SF (Qin et al., 2005). Plant phosphorus (P) concentration was directly related to P availability to the root system in maize seedlings before the V2 stage (Chassot and Richner, 2002). Researchers in Switzerland showed that root length density increased in the banded N and P fertilized zone located 5 cm to the side and 5 cm below the seed (5×5) (Chassot et al., 2001) which was similar to the results of Anghinoni and Barber (1988) in that root length density was greater in the fertilized zones. Root studies show that roots proliferate in fertilized soil zones; scientists suggest that injecting fertilizer into the soil may be preferable compared to surface broadcast fertilizer applications that were not incorporated into the soil because roots near the fertilized subsurface zones would be less susceptible to root drying and thus the banded fertilizer would be more available to the plant (Kaspar et al., 1991).

Researchers in Iowa found that hybrids did not yield differently to SF applications Buah et al., (1999); conversely, researchers in Kansas and Florida found differential hybrid biomass and grain yield responses to SF (Gordon et al., 1997; Gordon and Pierzynski, 2006; Rhoads and Wright, 1998; Teare and Wright, 1990). Gordon et al., (1997) found that hybrids yielded differently in response to SF applications and speculated that rooting differences among hybrids may influence the response. Gordon and Pierzynski, (2006) measured root growth at the V6 growth stage using a soil core method and found that hybrids that did not respond to SF had greater total root counts and rooted deeper when no SF was applied than hybrids that responded to SF. Greenhouse studies conducted with hybrids that showed response to SF in field research found that hybrids responded similarly to P based SF, conversely, hybrids with smaller root systems without SF responded to N SF in above and below ground growth while hybrids with larger root systems (as before) did not respond to N SF application (Rhoads and Wright, 1998). The authors suggested that hybrid responsiveness to N SF could be used to classify hybrid response to SF and used by farmers as a part of their management plan (Rhoads and Wright, 1998). Currently farmers consider applying SF to increase early-season growth of corn in high-residue situations with the belief that SF increases root size between V2 and V4; the thought is that larger plants are less susceptible to disease and stress in early-growth. To our knowledge, Iowa field research on early-season corn root growth in response to SF has not been performed.

Our overall objective in these studies was to determine whether hybrids and seeding rates responded to SF differently. Here specifically we wondered if hybrids and seeding rates did respond to SF differently, were differences in hybrid root systems also reflected in these differences that affected responses to SF.

Materials and Methods

We conducted root growth experiments in fields at the Agricultural Engineering and Agronomy Farm near Ames, IA during 2011 and 2012. Research was conducted on the same plots as other SF research (Pierson et al, 2013a, 2013b). Plots were located at 42° 01′ 55” N, 93° 78′ 72” W, and the major soil class was Clarion loam soil with 2 to 5% slope in 2011 and moved to 42° 01′ 07” N, 93° 73′ 97” W on 41% and soil classes consisted of Canisteo silty clay loam and 37% Clarion loam soil with 0 to 2% slopes in 2012. We planted on 4 May 2011 and 26 April 2012. The cropping system was continuous corn with tillage of one-pass fall chisel plow and one-pass spring field cultivation. Plots were planted with a Kinze planter with chain driven finger pickup meters and were 15.2 m long and six, 0.76 m rows wide. The planter was equipped a liquid SF applicator using angled coulters to place fertilizer 5×5 and fixed row cleaners. Treatments were arranged in a complete factorial, replicated four times, and the experimental design was a randomized completed block. Treatments consisted of varied seeding rate, hybrid, and with and without SF. We used a liquid SF treatment consisting of 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 $kg \cdot ha^{-1}$. Nitrogen was side dressed post emergence as 28% urea ammonium nitrate at a rate of 224.1 $kg \cdot ha^{-1}$ at approximately V4 (Abendroth et al, 2011) to all plots. We applied more N than recommended by Iowa State University Extension so that the SF would not increase yield due to fertility limitations in the non- fertilized plots (Iowa State University, 2013). Herbicides included both pre-plant and post planting chosen according to Iowa State University Extension recommendations. Hybrids provided by DuPont Pioneer International

(Johnston, IA) included PO448XR, PO461XR, and PO463XR and will be discussed as hybrid 1, 2 and 3, respectively. Hybrids had cumulative relative maturity of 104, 104, and 103 days respectively, and a range of root strength ratings including 7, 8, and 5, respectively, based on a scale of 1 – 9 with the higher numbers designating stronger root systems as defined by DuPont Pioneer International. Root strength ratings were developed by visually measuring stand ability after mechanical wind damage to plants. Differing root strength ratings were used to select hybrids that could possibly vary in root growth. Seeding rates were 74.1×10^3; 88.9×10^3; and 103.7×10^3 seed·ha^{-1}. Soil samples were taken at 0 to 15 cm depths in each replication before planting and postharvest. Emergence was calculated as the average of 10 selected plants in rows four and five.

Biomass Data Collection

We destructively sampled five consecutive randomly selected plants at approximately V2 and V4 both years. Sampling dates at V2 were 123 and 153 growing degree days (GDDs) after seeding in 2011 and 2012 respectively, and 250 and 221 GDDs after seeding for V4 samplings in 2011 and 2012 respectively. Growing degree days were calculated using information compiled from the Iowa Environmental Mesonet and GDDs were calculated in °C (IEM, 2013). Plant heights for these plants were measured using the ‘extended-leaf method’ in which each plant is measured from soil to the tip of the uppermost fully extended leaf at V2 and V4. We also measured stem diameter of these plants on the widest part of the elliptical stalk with a digital electronic caliper approximately 1.25 cm above soil level at V2 and V4. After that on the same day, we dug approximately 15 cm on both sides of the row of five consecutive plants and the end of the row of plants at an angle of approximately 60° from the soil surface. We sifted the soil by hand to remove soil from plant roots and placed the plants with roots in tagged paper bags. The following day we washed excess soil from roots, clipped the shoot from the roots approximately 1.9 cm above where the mesocotyl ends and coleoptile begins (Abendroth et al., 2011), and placed in roots of the group of untagged plants individually in a marked plastic bag at V2 and V4 while the shoot was placed in a paper marked bag. Plants were oven dried at 60 °C until constant weights were attained, and biomass measurements were recorded per plant.

Root Data Collection

We placed the roots in a cooler at 5 °C until they were scanned electronically. Seeds and soil remaining on the roots were removed before scanning to reduce the variation in root parameters caused by differences in seed size and soil. Roots were rinsed with water, placed in a translucent tray with the roots being separated by hand or with tweezers if necessary to ensure that roots were not overlapping for better analysis. Roots were scanned using an EPSON Flatbed Scanner EPSON Perfection V700/V750 1.8 V3.24 and analyzed using WinRHIZO (Regent Instruments, Quebec, Canada, 2008). Settings for analysis included: Pixel classification on grey scale and pale root on black background, professional mode, document type – reflective, image type – 8-bit greyscale, resolution – 400 dpi, trimming off, and unsharp mask off. Factors analyzed and recorded were root length, surface area, root diameter, number of tips, and number of forks. After scanning, roots were placed in marked paper bags, oven dried at 60 °C until constant weights were attained; then root biomass measurements were recorded on a per plant basis. Root: shoot ratio was calculated per destructively sampled plant.

Statistical Analysis

Analysis of variance was performed using the PROC MIXED procedure of the SAS software package, version 9.2 (SAS Institute, Cary, NC). Treatments were considered different when $P \leq 0.05$. Treatment differences were separated using the LSMEANS statement of the PROC MIXED procedure of SAS (SAS institute, Cary, NC). Years were initially analyzed combined, however, years were significant and caused interactions; therefore years were analyzed separately. All treatment factors were considered fixed, including SF, population density, and hybrid, whereas replications were treated as random.

Results

Phosphorus soil tests were optimum to high in 2011 and very low to low in 2012 (Sawyer et al., 2002). Both years had less accumulated precipitation than the 26-year average; 2012 was a drought year in the Midwest (Taylor, 2012) (Figure 1A). In 2011, GDDs accumulated less than the 26-year average, while in 2012, growing degree day accumulation was more than the 26-year average (Figure 1B). Days from planting to emergence was not affected by SF in either year (Table 1). However, hybrid 2 emerged later than the others in 2011 and hybrid 3 emerged later than the others in 2012 (Table 1).

Starter fertilizer increased root diameter only at the V2 stage and by 0.01 mm in 2012 (Table 2). Increasing seeding rate above 88.9×10^3 seeds$\cdot$ha^{-1} resulted in smaller root length, surface area, root tips, and number of forks at V4 in 2011 (Table 2). The lowest seeding rates - 74.1×10^3 seeds$\cdot$ha^{-1} - had larger root diameters than higher seeding rates at V4 both years (Table 2). The highest seeding rate had fewer root tips than the lower seeding rates at V4 in 2011 (Table 2). Root length and surface area were smaller for hybrid 3 than hybrids 1 and 2 at both samplings in 2012 (Table 2). Hybrid 3 had smaller root diameters than hybrids

1 and 2 at V4 both years (Table 2). In 2012 at V2 and V4 stages, root tip numbers were less for hybrid 3 compared to hybrids 1 and 2 (Table 2). Hybrids varied for number of root forks at V2 in 2012 and decreased in the order of hybrid 1, 2, and 3 (Table 2). By V4 in 2012 hybrid 3 had fewer root forks than hybrids 1 and 2 (Table 2). Starter fertilizer increased root biomass by 0.1 g in 2012 at the V2 sampling (Table 2). Root biomass increased with SF at V4 by 0.03 g in 2011 and 0.04 g in 2012 (Table 2). Root biomass at the V4 sampling in 2011 and 2012 was smaller at 103.7×10^3 seeds·ha^{-1} compared to lower seeding rates (Table 2). Increasing seeding rate from above 88.9×10^3 seeds·ha^{-1} resulted in smaller root biomass at V4 in 2012 (Table 2). Hybrids 1 and 2 had greater root biomass than hybrid 3 at V4 in 2012 (Table 2). Hybrid 2 had a less root biomass at V2 in 2011 than hybrids 1 and 3 (Table 2). In 2012, at both samplings, hybrid 3 had less root biomass than either hybrids 1 or 2 (Table 2).

In 2012 at the V2 sampling, SF increased shoot biomass at the 74.1×10^3 seeding rate by 0.07 g but it did not affect shoot biomass at the higher seeding rates (data not shown). Thus, the shoot biomass response to SF at V2 in 2012 shown in Table 3 is due only to the response at the lowest seeding rate. Hybrids responded differently to SF for shoot biomass at V4 in 2011; hybrid 1 and 2 increased shoot biomass by 0.25 and 0.20 g (35.2% and 25.6%) respectively with SF, however, SF did not increase shoot biomass for hybrid 3 (Table 4). However, shoot biomass of hybrid 3 without SF was similar to shoot biomass of hybrids 1 and 2 with SF. Following the same pattern as shoot biomass, root biomass for hybrid 3 with and without SF was similar to the root biomass of hybrids 1 and 2 with SF (Table 4). The root: shoot ratio for hybrid 3 with starter was larger than without, while the other hybrids did not change (Table 4). Hybrid 1 responded to SF by increasing height at V4 while hybrids 2 and 3 did not in 2011 (Table 4). In contrast, hybrid 2 was shorter with SF applied at V2 in

2011 (Table 4). At V4 in 2012, hybrids responded differently to increasing seeding rates for height, stem diameter, and shoot and root biomass (Table 5). Hybrid 3 at the 88.9 x 10^3 seeding rate appeared to be an outlier with all values deviating from those of the other hybrids potentially causing the significant interactions (Table 5).

Discussion

Starter fertilizer and seeding rates had no effect on emergence dates as expected because SF was placed 5×5 and should not affect the seedling until root systems are more developed. However, hybrids varied in their emergence dates in years (Table 1); we expected a response similar to 2012 in that the hybrid with stronger root strength ratings by DuPont Pioneer would emerge sooner, however this was not the case in 2011. Hybrid 3 had similar emergence to hybrid 1, while hybrid 2 emerged later in 2011, therefore, root strength ratings may not be strongly related to emergence date. Hybrids varied in their root growth in both years; a trend toward hybrid 3 having smaller root lengths, diameter, surface area, and root biomass existed at all samplings in 2012. The same hybrid had less root forks and root tips; while all hybrids produced different root forks at V2 in 2012. Hybrid 3 also had an average emergence later in 2012; this characteristic substantiates hybrid differences in root strength ratings according to DuPont Pioneer. Rhoads and Wright (1998) and Gordon and Pierzynski (2006) found that hybrids with smaller root systems were more likely to respond to SF. In 2011 hybrids 1 and 2 had smaller root biomass without SF, responded to SF, while hybrid 3 did not respond to SF but had a root system of similar size to the fertilized hybrids that responded to SF (Table 4). Hybrid 3 did not respond to SF by increasing above-ground biomass in 2011, however, did respond that way in 2012. This was different than we expected; we expected hybrids with lower root strength ratings to respond to SF, however, root strength ratings may not be related to early root growth and response to SF. Differences in response could have been due to warmer soil temperatures in 2012 at planting causing emergence to occur faster.

Increasing seeding rates from 74.1 × 10^3 seeds·ha^{-1} to 88.9 and 103.7 × 10^3 seeds·ha^{-1} resulted in smaller individual plant root diameters at V4 both years. Increasing seeding rates from 74.1 and 88.9 × 10^3 seeds·ha^{-1} to 103.7 × 10^3 seeds·ha^{-1} resulted in smaller root measurements for all parameters at V4 in 2011 and for root biomass at V4 in 2012. Competition for light was likely a factor for above ground biomass; increasing seeding rates resulted in light competition as suggested by (Hebert et al., 2001). Although plant heights were only different among seeding rates at V4 in 2011, stem diameter was smaller both years at V4 with increased seeding rates (Table 3). Starter fertilizer did not increase shoot biomass at the V2 sampling in 2012 for the 88.9 and 103.7 × 10^3 seeds·ha^{-1} but at 74.1 × 10^3 seeds·ha^{-1}; the trend also occurred with root biomass. Competition among plants at the higher seeding resulted in a trend of smaller root characteristics at V4 than the low seeding rate (Table 2) potentially allowing the plant roots in the low seeding rate to interact with SF and respond sooner.

Root biomass increased with SF at V2 in 2012 and V4 in both years at a proportion similar to the increase in above ground biomass. The increase in both root and shoot biomass in response to SF at the V2 sampling in 2012 may be related to greater root lengths with warmer soil temperatures (Logsdon et al., 1987; Mengel and Barber, 1974). Soil temperatures at 10cm depths at average emergence date (day 0) and days 1 to 3 after emergence were approximately 18.3, 14.4, 11.7, and 11.1 °C in 2011 respectively, and 21.1, 20.0, 17.8, and 15.6 °C, respectively for days 0 to 3, in 2012 according to the Iowa

Environmental Mesonet (IEM, 2013). Also, more GDDs accumulated after seeding in 2012, so the plants may have been more developed at the V2 sampling in that year; exact data was not collected. While some studies have focused on root growth within the fertilized zone (Chassot et al., 2001), our root system sampling methodology does not allow us to do so, however, it does allow us to collect the entire roots system at the early stages of growth.

Root and shoot growth varied both years with hybrids and seeding rates; hybrid 3 – the hybrid with the lowest root rating - did not respond to SF in shoot biomass at the V4 sampling in 2011. Also, seeding rates responded differently to SF in that the higher seeding rates tended to have smaller root characteristics. Differential response to SF and increased seeding rate may be related to smaller root characteristics with increased plant-to-plant competition for resources.

Others have shown that early-season growth responses to SF are not good indicators of grain yield responses (Kaiser et al., 2005). However, early-season growth affects grain yield factors such as number of kernel rows per ear (Abendroth et al., 2011). Extreme environmental stress in early-season growth may limit this yield component. Low soil temperatures and soil moisture stresses plants during early-season growth. The soil environment is also affected by residue remaining on soil with reduced tillage systems. Nutrient placement near the seed increases early-season growth and may reduce stress at critical grain determination periods.

Conclusion

Hybrids and seeding rates varied in their response to SF as measured by root variables. A hybrid with larger plant and root biomass without SF did not respond to SF. This hybrid had similar plant and root biomass to hybrids that responded to SF when SF was applied in 2011. The hybrid response to starter fertilizer occurred once; the response was not consistent with our other study discussed in chapter 2 in that estimated biomass response to SF did not differ by hybrid, (Pierson et al., 2013), and did not occur for grain yield. The low seeding rate tended to have larger root characteristics at V2 in 2012 and responded to SF application in plant shoot biomass, which was potentially due to more rapid contact with the band of SF. By the V4 samplings, root characteristics such as length, surface area, diameter, number of tips and forks were smaller at the higher seeding rates in 2011 and root diameter and biomass were smaller in 2012. Differences in hybrids and seeding rates root and shoot growth and developmental characteristics may alter the response or timing of response to SF applications.

Table 1. Starter fertilizer, seeding rate, and hybrid differences in days from seeding to emergence. Data presented in this table was presented previously in Pierson et al, (2012 a).

Year	Starter	Emergence Days after seeding
2011	Yes	8.42 a‡
	No	8.41 a
2012	Yes	9.16 a
	No	9.19 a
	Seeding Rate (Seeds·ha^{-1})	
2011	$74,1 \times 10^3$	8.45 a
	88.9×10^3	8.39 a
	103.7×10^3	8.40 a
2012	74.1×10^3	9.20 a
	88.9×10^3	9.14 a
	103.7×10^3	9.19 a
	Hybrid	
2011	1†	8.31 a
	2	8.58 b
	3	8.36 a
2012	1	9.17 a
	2	9.10 a
	3	9.25 b

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.

‡ Means between treatments within a year followed by the same letter are not different ($P \leq 0.05$).

Table 2. Root characteristics plant^{-1} and root biomass per plant at two developmental stages varied by hybrid, seeding rate, and starter fertilizer treatments in 2011 and 2012 at Ames, IA. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}.

Year	Developmental stage	Starter fertilizer	Length (cm)	Surface area (cm^2)	Diameter (mm)	Number of tips	Number of forks	Root biomass (g·plant^{-1})
2011	V2	Yes	51 a‡	8 a	0.63 a	260 a	100 a	0.12 a
		No	49 a	8 a	0.51 a	250 a	100 a	0.12 a
	V4	Yes	93 a	17 a	0.59 a	310 a	160 a	0.23 a
		No	91 a	17 a	0.59 a	300 a	150 a	0.20 b
2012	V2	Yes	65 a	10 a	0.47 a	330 a	110 a	0.10 a
		No	65 a	9 a	0.46 b	340 a	110 a	0.09 b
	V4	Yes	76 a	14 a	0.58 a	310 a	150 a	0.21 a
		No	74 a	13.0 a	0.57 a	300 a	140 a	0.17 b
		Seeding rate ha^{-1}						
2011	V2	74.1×10^3	52 a	8 a	0.50 a	270 a	100 a	0.12 a
		88.9×10^3	48 a	8 a	0.70 a	250 a	100 a	0.13 a
		103.7×10^3	50 a	8 a	0.51 a	250 a	100 a	0.12 a
	V4	74.1×10^3	96 a	18 a	0.61 a	320 a	170 a	0.24 a
		88.9×10^3	96 a	18 a	0.58 b	330 a	170 a	0.22 a
		103.7×10^3	84 b	15 b	0.58 b	280 b	140 b	0.19 b
2012	V2	74.1×10^3	65 a	9 a	0.46 a	330 a	110 a	0.10 a
		88.9×10^3	67 a	10 a	0.47 a	330 a	100 a	0.09 a
		103.7×10^3	64 a	9 a	0.47 a	340 a	110 a	0.09 a
	V4	74.1×10^3	74 a	14 a	0.60 a	290 a	150 a	0.21 a
		88.9×10^3	77 a	14 a	0.57 b	320 a	150 a	0.19 a
		103.7×10^3	73 a	13 a	0.56 b	300 a	140 a	0.17 b
		Hybrid						
2011	V2	1†	51 a	8 a	0.7 a	260 a	100 a	0.13 a
		2	48 a	7 a	0.5 a	250 a	90 a	0.11 b
		3	50 a	8 a	0.5 a	260 a	100 a	0.13 a
	V4	1	95 a	18 a	0.59 a	310 a	160 a	0.21 a
		2	88 a	17 a	0.60 a	310 a	150 a	0.22 a
		3	93 a	17 a	0.58 b	310 a	160 a	0.22 a
2012	V2	1	68 a	10 a	0.5 a	340 a	120 a	0.10 a
		2	68 a	10 a	0.5 a	360 a	110 b	0.10 a
		3	61 b	9 b	0.5 a	300 b	90 c	0.09 b
	V4	1	78 a	14 a	0.59 a	310 a	150 a	0.21 a
		2	75 a	14 a	0.59 a	320 a	150 a	0.19 a
		3	71 b	12 b	0.56 b	280 b	130 b	0.17 b

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.
‡ Means within the same column, year, and stage followed by the same letter are not different ($P \leq 0.05$).

Table 3. Shoot characteristics including height, stem diameter and shoot biomass varied by treatments including starter fertilizer, seeding rate, and hybrid in 2011 and 2012 at Ames, IA. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}.

Year	Stage	Starter fertilizer	Height (cm·plant^{-1})	Stem diameter (mm·plant^{-1})	Biomass (g·plant^{-1})
2011	V2	Yes	10.5 a‡	2.4 a	0.09 a
		No	10.5 a	2.4 a	0.09 a
	V4	Yes	33.0 a	7.6 a	0.92 a
		No	30.8 b	7.4 a	0.80 b
2012	V2	Yes	17.0 a	3.9 a	0.27 a
		No	16.4 a	3.7 b	0.24 b
	V4	Yes	27.9 a	7.4 a	0.90 a
		No	25.0 b	6.6 b	0.69 b
		Seeding rate ha^{-1}			
2011	V2	74.1×10^3	10.4 a	2.4 a	0.09 ab
		88.9×10^3	10.7 a	2.4 a	0.10 a
		103.7×10^3	10.4 a	2.4 a	0.09 b
	V4	74.1×10^3	33.0 a	7.9 a	0.97 a
		88.9×10^3	31.9 ab	7.5 ab	0.85 ab
		103.7×10^3	30.8 b	7. 0 b	0.75 b
2012	V2	74.1×10^3	16.6 a	3.9 a	0.26 a
		88.9×10^3	16.6 a	3.8 a	0.25 a
		103.7×10^3	16.9 a	3.8 a	0.25 a
	V4	74.1×10^3	27.5 a	7.4 a	0.88 a
		88.9×10^3	26.1 a	6.9 ab	0.78 ab
		103.7×10^3	25.8 a	6.6 b	0.73 b
		Hybrid			
2011	V2	1†	10.6 a	2.5 a	0.10 a
		2	9.9 b	2.4 a	0.09 b
		3	11.1 a	2.4 a	0.09 b
	V4	1	31.8 a	7.4 a	0.83 a
		2	32.3 a	7.7 a	0.88 a
		3	31.5 a	7.3 a	0.86 a
2012	V2	1	17.0 a	3.9 a	0.28 a
		2	16.8 a	4.0 a	0.26 a
		3	16.3 a	3.6 b	0.23 b
	V4	1	27.4 a	7.3 a	0.88 a
		2	26.0 a	6.9 ab	0.77 ab
		3	26.0 a	6.7 b	0.74 b

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.
‡ Means within the same column, year, and developmental stage followed by the same letter are not different ($P \leq 0.05$).

Table 4. Hybrid responses to starter fertilizer as reflected in physical parameters of plants at V2 and V4 in 2011. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}.

Hybrid	Starter fertilizer	V2 plant height	V4 plant height	V4 Stem diameter	V4 Shoot biomass (g·plant^{-1})	V4 Root biomass (g·plant^{-1})	Root: shoot ratio
1†	Yes	10.7 ab ‡	34.1 a	7.9 a	0.96 a	0.24 a	0.26 a
	No	10.5 b	29.5 b	7.0 b	0.71 b	0.19 b	0.28 ab
2	Yes	9.6 c	33.5 ac	7.9 a	0.98 a	0.24 a	0.25 a
	No	10.2 b	31.2 bc	7.4 ab	0.78 bc	0.20 b	0.26 ab
3	Yes	11.1 a	31.4 bc	7.0 b	0.82 c	0.22 a	0.29 b
	No	10.8 ab	31.8 ac	7.6 a	0.89 ac	0.21 ab	0.25 a

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.

‡ Means within the same column followed by the same letter are not different.

Table 5. Hybrid responses to increased seeding rate as reflected in height, stem diameter, root and shoot biomass measurements at V4 in 2012. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}.

Hybrid	Seeding rate	Plant height V4 (cm)	Stem diameter V4(mm)	Shoot biomass (g·plant^{-1})	Root biomass (g·plant^{-1})	Root: shoot ratio
1†	74.1×10^3	27.1 a‡	7.3 ab	0.89 ab	0.22 a	0.28 a
	88.9×10^3	28.4 a	7.6 a	0.94 a	0.22 a	0.24 a
	103.7×10^3	26.6 a	7.0 ab	0.82 ab	0.19 ab	0.25 a
2	74.1×10^3	27.4 a	7.4 a	0.85 ab	0.19 ab	0.24 a
	88.9×10^3	26.6 a	7.2 ab	0.85 ab	0.21 a	0.26 a
	103.7×10^3	24.1 b	6.1 cd	0.61 c	0.16 c	0.27 a
3	74.1×10^3	28.1 a	7.5 a	0.91 a	0.21 a	0.24 a
	88.9×10^3	23.2 b	5.8 d	0.56 c	0.15 c	0.29 b
	103.7×10^3	26.7 a	6.7 cb	0.75 b	0.17 bc	0.25 a

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.
‡ Means within the same column followed by the same letter are not different ($P \leq 0.05$).

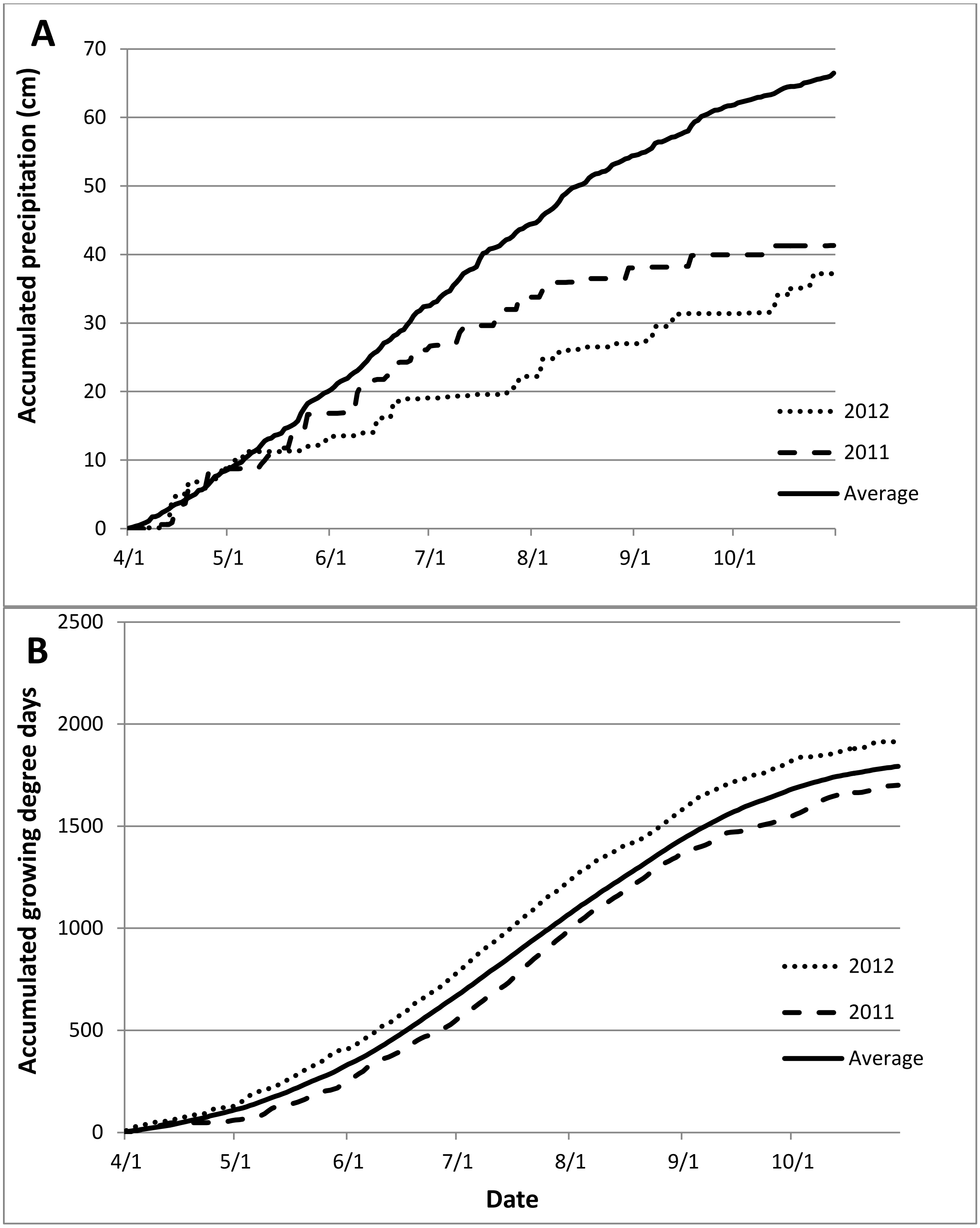

Figure 1. Accumulated precipitation (**A**) and growing degree days (**B**) for the growing seasons of 2011, 2012, and the 26-year averages (cm). Ames, IA.

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CHAPTER 4: EFFECT OF STARTER FERTILIZER ON SEEDING RATES AND CORN HYBRIDS PLANT-TO-PLANT VARIABILITY IN GROWTH AND GRAIN YIELD

A paper in preparation for *Agronomy Journal*

Abstract

Plant-to-plant variability in corn (*Zea mays* L.) induced by variability in emergence and growth negatively affects grain yield. Farmers have asked if starter fertilizer (SF) reduces plant-to-plant variability by making nutrients more uniformly available to plants early in the season. The objectives of this study were to determine if SF affects plant-to-plant variability in growth of corn. If SF affected plant-to-plant variability of growth in corn, we wanted to determine if plant-to-plant variability in growth also affects variability in grain yield plant^{-1} and grain yield ha^{-1}. We used three hybrids, three seeding rates, and with and without SF to provide a range of competition that affects plant-to-plant variability. Similar experiments were performed near Ames, IA and Nashua, IA in 2011 and 2012 with differences in quantity of measurements, tillage systems, and crop rotations. We measured plant height, stem diameter, and destructively sampled plants for biomass to create models that estimate biomass at various stages. We also calculated the coefficient of variation (CV) as a measure of variability. Starter fertilizer increased plant-to-plant variability in plant growth and grain yield at the low seeding rate in 2011 at Ames, IA. Plant-to-plant variability in plant growth was reduced at V6 with SF at the high seeding rate in 2011. Hybrids responded to seeding rates differently in 2012 in plant-to-plant variability in plant growth and grain yield at Ames, IA. Increased variation in plant-to-plant variability in growth and grain yield was negatively correlated to yield ha^{-1} in 2012 but not in 2011. Effects of plant-to-plant

variability in 2011 was not enough to cause yield loss but the addition of moisture stress in 2012 likely resulted in yield loss related to plant-to-plant variability. Starter fertilizer increased plant-to-plant variability in growth at the low seeding rate in 2011. Variability in growth did translate into variability in grain yield both years. Variability in plant growth and plant grain yield were correlated to yield loss in 2012, but not in 2011. Differences in environmental stress are likely related to variability in plant growth and grain yield affecting yield per area.

Introduction

Corn grain yield ha^{-1} improvement has occurred by increasing seeding rates and by breeding hybrids that are more tolerant to plant density stress and advanced agronomic management practices (Tollenaar and Lee, 2002; Tollenaar and Wu, 1999). Competition among corn plants for the same water, nutrients, and light generally results in lower grain yield per plant (Nafziger, 2006); however, grain yield per unit area increases with more plants per unit area until resources become limited. Scientists often measure corn plant-to-plant variability using the coefficient of variation (CV) (Glenn and Daynard, 1974), where:

CV = (sample standard deviation / sample mean)

Corn seed spacing uniformity has often been studied in conjunction with plant-to-plant variability. Results of these studies have varied with advancing technology such as planter type including finger pickup meters, vacuum meters, and air seeding systems. In a 1972 study, grain yield decreased with increased plant spacing standard deviation (Krall et al., 1977). In another study, agronomists found a 0.39 Mg·ha^{-1} loss for each 2.54 cm increase in plant spacing standard deviation (Nielsen, 2001). Other agronomists used an air seeder to determine whether farmers could use equipment designed for other crops to plant corn. They found that a plant spacing standard deviation that was 2 to 3 times higher than with vacuum meter and finger pickup meter planters. With the air seeder, average yields were reduced 0.0359 $Mg \cdot ha^{-1}$ for each cm increase plant spacing standard deviation (Liu et al., 2004a). In a Wisconsin commercial field study, plant spacing standard deviations greater than 12 cm resulted in yield losses (Lauer and Rankin, 2004). However, standard deviations that high were not common in farmer fields and would require many abnormal gaps and doubles (Lauer and Rankin, 2004). Other studies have shown no yield reductions with increasing plant spacing standard deviations (Glenn and Daynard, 1974; Liu et al., 2004c). Some agronomists suggest that uniformity in seeding depth, seedbed preparation, and seedling vigor may minimize variation in seedling size which may be more important than spacing standard deviation (Muldoon and Daynard, 1981).

Factors such as soil crusting, herbicides, soil compaction, low soil moisture and temperature, and variable seeding depth affect emergence timing and variability (Alessi and Power, 1971; Nafziger et al., 1991). Late emerging and shorter plants are at a disadvantage compared to earlier emerging and taller plants due to competition for resources (Edmeades and Daynard, 1979; Ford and Hicks, 1992; Tollenaar and Wu, 1999). Plant yields with development delays were lower and were never offset by increased yield of neighboring plants thus causing yield loss among groups of 6 plants (Liu, et al., 2004b). When time to 50% emergence was delayed by more than 3 days, yield losses amounted to 292.8 kg $ha^{-1}d^{-1}$ (Liu et al., 2004a). Nafziger et al., (1991) showed that replanting due to variable emergence delays of up to 2 weeks were not likely to be economical; however, when 25% of the plants were delayed by 3 weeks or more, they suggested replanting may be justified. Similar to these results, other agronomists showed that plants that were planted 2, 5, and 8 days after others were able to compete with earlier planted plants; but plants that were planted 12 days after others were unable to compete with neighboring plants planted earlier (Lawles et al., 2012). Grain yield reductions of 0.225 to 1.379 $Mg \cdot ha^{-1} \cdot day^{-1}$ occurred for each day delay in emergence (Lawles et al., 2012).

Researchers sometimes develop allometric biomass models - models developed using parameters such as stem diameter and height to estimate biomass - to estimate plant-to-plant variability in growth (Maddonni and Otegui, 2004). They divided plants into categories considered dominate and dominated plants; dominate plants were in the top 1/3 and dominated plants in the bottom 1/3 of estimated plant biomass. Maddonni and Otegui, (2004) found that plant-to-plant variability differed in estimated plant biomass for plant densities as early as V4 to V7 (Abendroth et al, 2011) and the greatest difference between dominate and dominated plants occurred between V7 and V13. By tracking growth of individual plants, they found that dominant plants always produced more kernels than dominated ones, however, the authors did not discuss yield per unit area (Maddonni and Otegui, 2004). In another study, the same authors found that as stand density increased, individual plant biomass at R6 and plant yield decreased; however, dominated plants had greater reductions with higher densities than dominant plants (Maddonni and Otegui, 2006). Other agronomists found that dominated plants yielded less because of less available assimilate per ear and spikelet around silking – R1- which increased the anthesis silking interval (ASI) and delayed silk emergence (Pagano et al., 2007). A hybrid less tolerant to crowding had the highest plant-to-plant variability of shoot biomass; this variability was negatively related to assimilate partitioning to the ear during grain fill and reduced kernel numbers (Pagano and Maddonni, 2007). Other researchers found that dominated plants responded more to additional nitrogen, urea broadcast immediately after planting, which led to less plant grain yield variability within a stand (Caviglia and Melchiori, 2011).

Hybrids that differed in plant-to-plant variability of plant growth rates also varied in kernel number and grain yield at two nitrogen (N) rates applied at approximately V6; hybrids with high N supply had reduced kernel weight variability (Mayer et al., 2012). Increasing plant-to-plant variability in plant height, ear height, and ear length were related to increasing plant density (Tokatlidis et al., 2005). A study conducted at various locations in the USA, Argentina, and Mexico reported that increasing plant yield CV was negatively correlated to total grain yield; however, sites with the highest yield had greater per plant yield CV than sites at lower yield levels (Martin et al., 2005). The authors concluded that methods to make corn more uniform in emergence and growth could increase yield. Some research studies focused on timing of plant removal to determine when competition affects plant yield. Competition before V5 had the least effect on yield, while competition during the rest of the season had the largest negative effect on grain yield (Hashemi et al., 2005). Another study showed that plant removal at V9 did not result in compensation by remaining plants (Pagano and Maddonni, 2007). Early-season growth variability may affect grain-yield variability but this may be mitigated by management practices that reduce disparity in early growth; these might include uniform seed depth, planting at proper soil temperature and moisture, and uniform nutrient placement.

Starter fertilizer (SF) often increases early corn growth. Early-season growth responses to starters have occurred with soils testing high for phosphorus (P), however, larger responses occurred with low - P soil tests (Bermudez and Mallarino, 2002). The main objective of this study is to determine if SF affects corn plant-to-plant variability. Then, if plant variability does occur, we wanted to determine if plant-to-plant variability in corn growth resulted in plant-to-plant variability in individual plant grain yield and growth and grain yield on an area basis. We are not aware of others who have investigated SF from this perspective.

Materials and Methods

Two similar experiments were conducted near Ames, IA and Nashua, IA during 2011 and 2012 to measure plant-to-plant variability in growth and grain yield. Research was conducted on the same plots as other SF research (Pierson et al, 2013a, 2013b). Although similar measurements were recorded, experiments were treated as separately because locations had different crop rotations and tillage systems. Furthermore, environments differed with years; rainfall was substandard at both Ames and Nashua with drought in 2012 (Figure 1a, b). Accumulated growing degree days were below average at Ames in 2011 (Figure 2a) but greater than average in 2012 at both locations (Figure 2a, b).

We conducted field experiments at the Agricultural Engineering and Agronomy Farm near Ames, IA Plots were located at 42° 01′ 55” N, 93° 78′ 72” W, on a Clarion loam soil with 2 to 5% slope in 2011 and moved to 42° 01′ 07” N, 93° 73′ 97” W on 41% Canisteo silty clay loam and 37% Clarion loam soil with 0 to 2% slopes in 2012. Plots were planted 4 May 2011 and 26 April 2012. Field experiments were also conducted at the Northeast Research and Demonstration Farm at Nashua near Nashua, IA during 2011 and 2012. Plots were located at 42° 92′ 97” N, 92° 57′ 63” W in 2011 and 42° 93′ 05” N, 92° 57′ 68” W in 2012 on Floyd loam soils with 1 to 4 % slopes. Plots were in 2012 were directly north of plots in 2011; the plot areas were managed similarly in a corn-soybean rotation. Plots were planted 13 April 2011 and 24 April 2012.

Ames, Iowa

Field History, Operations, and Treatments

Corn was the previous crop in both years; tillage consisted of one-pass fall chisel plow and one-pass spring field cultivation. Plots were 15.2 m long and consisted of six 0.76 m rows planted with a Kinze planter using chain driven finger pickup meters. The planter was equipped with a ground driven liquid SF applicator using angled coulters to place fertilizer 5 cm below and 5 cm to the side of the seed (5×5) and fixed row cleaners. The experimental design was a randomized completed block with treatments arranged in a complete factorial and replicated four times. Treatments included 3 seeding rates, 3 hybrids, and with and without SF. We used a liquid SF treatment consisting of 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 $kg \cdot ha^{-1}$. Nitrogen (N) was side dress applied post emergence as liquid 28% urea ammonium nitrate at a rate of 224.1 $kg \cdot ha^{-1}$ at approximately V4 to all plots (Abendroth et al, 2011). We applied more N than recommended by Iowa State University Extension soil-fertility specialists so that the SF would not increase yield due to fertility limitations in the non-fertilized plots (Iowa State University, 2013). Herbicides included both pre-plant and post-emergence herbicides chosen according to Iowa State University Extension recommendations. Hybrids provided by DuPont Pioneer International (Johnston, IA) included P0448XR, P0461XR, and P0463XR and will be referred to as hybrid 1, 2, and 3 respectively from here on. Hybrids 1, 2, and 3 had root strength ratings of 7, 8, and 5 respectively and cumulative relative maturities of 104, 104, and 103 days, respectively. DuPont Pioneer International hybrid root-strength ratings are visually assessed and based on a 1 to 9 scale based on stand ability after mechanical wind damage. Seeding rates were 74.1, 88.9, and 103.7 x10^3 seeds·ha^{-1}. Soil samples were taken pre-plant and post-harvest. Samples were taken at 0 to 15 cm depths in each replication.

Biomass Data Collection

To estimate biomass we first designated plants as either tagged or untagged. Tagged plants included five consecutive plants in rows four and five (10 total). To choose these plants, we placed a stake between rows four and five, 3 m from the plot border and another stake 4 m from the plot border; plants between these stakes were marked with date of emergence noted on small stakes for each plant. We checked plant emergence daily from 5 to 20 days after planting. Stand counts were taken each of these days in rows four and five and recorded to calculate an emergence rate index (ERI) (Erbach, 1982):

$$\mathrm{ERI} = \sum_{n=\mathrm{first}}^{\mathrm{last}} \frac{[\,\%n - \%(n-1)]}{n}$$

where:
%n = percentage of plants emerged on day n
%(n-1) = percentage of plants emerged on day n-1
n = number of days after planting
first =number of days after planting that the first plant emerged (first counting day)
last = number of days after planting when emergence was considered complete (last counting day)

We report early-season plant population that corresponded with the final ERI stand counts; late-season plant populations were recorded after R6 but before harvest.

After all plants emerged, we marked the first five consecutive plants between the 3 m and 4 m stakes with numbered stakes, recorded emergence date, and hence forth these plants considered as 'tagged' plants. The tagged plants were measured throughout the season for biomass estimates. We will describe the measurements in the next paragraph. We randomly selected six groups of untagged plants that consisted of five consecutive plants in row two;

each group was spaced approximately 1.5 m apart to ensure that their removal would not impact growth of other groups to be harvested later. Untagged plants served as proxies for in-season biomass measurements for the tagged plants. Tagged and untagged plants were vegetatively staged using a modified version of the Iowa State University leaf collar method (Abendroth et al., 2011). This modification allows us to stage plants to 0.25 accuracy; we did this at approximately V4, V6, V9, and V15 in 2011 and V2, V4, V6, V9 and V15 in 2012. The 5th and 10th leaf were painted on all tagged and untagged plants to allow accurate staging after the lower leaves senesced and decomposed due to stalk expansion (Abendroth et al., 2011). After silking, plant spacing before and after tagged plants was measured and plant spacing standard deviation calculated per plot.

Plant heights for tagged and untagged plants were measured using the extended leaf method in which each plant is measured from soil to the tip of the uppermost fully extended leaf at development stages V2, V4, V6, V9, V15, and R2 (Table 1). We also measured stem diameter on the widest part of the elliptical stalk with a digital electronic caliper approximately 1.25 cm above soil level at V2, V4, and V6 and at a location centered between the 7th and 8th node at V9, V15, and R2. After measurements were taken, we dug the untagged plants we measured that day, washed roots, clipped the shoot from the roots at the soil surface, and placed in roots individually in a marked plastic bag at V2 and V4 while the shoot was placed in a paper marked bag. Untagged plants were cut at the soil surface at V6, V9, V15 and R2 and placed in a marked bag – no roots were dug or processed for these sampling times. Plants were oven dried at 60 °C until constant weights were attained, and biomass measurements were recorded per plant.

Plant Biomass Estimate Equations

Biomass equations (Table 2) were developed for each sampling date by correlating plant height and stem diameter measurements to biomass of destructively sampled untagged plants in order to estimate the biomass of tagged plants. Stem diameter was plotted against destructively sampled plant biomass and correlated to biomass in both linear and quadratic relationships. We used both linear and quadratic equations for stem diameter because generally both were similarly correlated and added strength to our model. Plant height was also plotted against destructively sampled plant biomass and correlated to biomass in a linear relationship. The PROC REG procedure of SAS software package, version 9.2 (SAS Institute, 2010) was used to develop equation parameters (Table 2). The equations developed appear as:

$$\text{Biomass} = x\,(\text{plant height}) + y\,(\text{stem diameter}) + z\,(\text{stem diameter})^2 + \text{intercept}$$

These equations were used to estimate the biomass at each sampling date of "tagged plants". To address plant-to-plant variability per treatment we used the coefficient of variation (CV) per plot for parameters such as estimated plant biomass and per plant grain yield.

$$\text{CV} = \text{sample standard deviation} / \text{sample mean}$$

Grain Yield Data Collection

We hand harvested individual ears after random samples from border rows had reached physiological maturity (R6) which was determined by checking plots until all randomly selected ear kernels had a visible black layer. We husked the ears of tagged plants and counted the number of kernel rows per ear. In 2011 the ears were hand shelled, while in 2012 a mechanical sheller was used; we recorded wet grain weight immediately after ears were shelled to limit drying of kernels. We oven dried grain at 60 °C until constant weights were attained, and recorded dry grain weight per plant. Grain yield from individually harvested plants was adjusted to 155 $g \cdot kg^{-1}$ moisture. We collected yield and moisture using a plot combine, and then adjusted to 155 $g \cdot kg^{-1}$ moisture. Yield from individually harvested plants was added to the combine harvested yield to obtain final plot yield. An electronic seed counter (The Old Mill Company and Model 850-2, International Marketing and Design Corp, San Antonio, Texas) was used to measure kernel number per ear.

Nashua, Iowa

Field History, Operations, and Treatments

Soybean (*Glycine max* L.) was the previous crop both years, and no tillage was performed prior to planting. Plots were the same size as at Ames and planted with a similar planter equipped with row cleaners and a dry SF applicator using angled coulters to place fertilizer 5×5. The experimental design, replication, and treatments were the same as at the Ames location. The dry fertilizer treatment was 11-52-0 (monoammonium phosphate) applied at a rate of 112.1 $kg \cdot ha^{-1}$. Nitrogen was applied before planting as anhydrous ammonia at a rate of 157 $kg \cdot ha^{-1}$ N. Hybrids and seeding rates were the same as those used at the Ames location. Soil samples were taken before planting and postharvest. Samples were taken at 0 to 15 cm depth in each replication.

Biomass Data Collection

Plants were characterized as tagged and untagged, and identified in a similar method as those at Ames. We checked the plots 2, 4, and 6 days after the first plants emerged and estimated earlier emergence dates based on plant size on those three days. Early-season plant populations were recorded after all plants emerged and late-season plant populations were recorded after maturity but before harvest. Sampling dates were approximately V3, V9, and

R2; sampling consisted of the same extended leaf height, stem diameter, and destructively sampling plants in row 2 for biomass as those at Ames. We created biomass models for tagged plants from untagged plants using these parameters similar to those at Ames (Table 2). Grain yield data was collected using the same method as explained in Ames discussion above.

Statistical Analysis

Analysis of variance was performed using the PROC MIXED procedure of the SAS software package, version 9.2 (SAS Institute, 2010). Treatment differences were separated using the LSMEANS statement of PROC MIXED (SAS Institute, 2010). Correlation between factors was compared using the PROC CORR procedure of SAS software package, version 9.2 (SAS Institute, 2010) which uses the Pearson correlation coefficient. Years were analyzed separately due to precipitation differences between years. All treatment factors were considered fixed, including SF, population density, and hybrid, whereas replications were treated as random. Treatments were considered different if $P \leq 0.05$ unless otherwise noted.

Results

Ames, Iowa

Phosphorus soil tests were optimum to high in 2011 and low to very low in 2012 (Sawyer et al., 2002). Emergence rate index differed among hybrids (Table 3), however, not affected by SF. In 2011, plant spacing standard deviations of hybrids varied with seeding rate and in 2012 plant spacing standard deviation was different for seeding rates (data not shown). Starter fertilizer had no effect on average emergence date in either year; however, hybrids emerged at different times and as expected, early-season plant populations correlated with seeding rates in both years (Table 3). Late-season stand counts were correlated to seeding rates in both years as expected, but were reduced by approximately 1.5 $\times 10^3$ plants·ha^{-1} with SF in 2011compared to an average of approximately 87 $\times 10^3$ plants·Ha^{-1} (Table 3).

Starter fertilizer increased early-season biomass and in addition, treatments that received SF developed more rapidly as we reported in our other work (Pierson et al, 2013). In 2011, at all sampling dates, SF increased plant-to-plant variability with 74.1 x 10^3 seeds·ha^{-1}, but decreased plant-to-plant variability with 103.7 x 10^3 seeds·ha^{-1} at V6 (Table 4). In 2011, plant-to-plant variability in growth at the lowest plant population translated into increased of plant-to-plant variability in grain yield plant^{-1} (Table 4). By V4 in 2012, hybrid responses varied with seeding rate for plant-to-plant variability that existed until R2 (Table 6); a similar trend in plant-to-plant variability for grain yield plant^{-1} CV existed, while hybrid 2 at the high seeding rate had much higher grain yield plant^{-1} CV (Table 6). Hybrid 2 generally had increased plant-to-plant variability with increased seeding rate; conversely, hybrids 1 and 3 had similar variability across all seeding rates (Table 6).

Increased variation in estimated plant biomass at R2 was negatively, but poorly (r = -0.023) correlated with reduced yield in 2011 (Figure 3a) (P = 0.85). In 2012, increased variation in estimated plant biomass at R2 was negatively (r = -0.37) correlated with reduced yields (Figure 3b) (P = 0.0013). Plant grain yield CV was not correlated to yield·ha^{-1} in 2011 (r = 0.00) (P = 0.99), however, increasing plant grain yield CV was negatively correlated to yield·ha^{-1} in 2012 (r = -0.42) (P = 0.0003) (Figure 4). Plant spacing standard deviation was negatively correlated to yield in 2011 (r = -0.30) (P = 0.0115) but not correlated to yield in 2012 (r = -0.00) (P =0.0003) (Figure 5). Starter fertilizer had no effect on emergence date;

however, trends in yield plant^{-1} in response to emergence date were different for the starter and no starter treatments (Figure 6). Yield plant^{-1} was negatively correlated with increasing days after emergence with SF (r = -0.37) (P < 0.0001) and without SF (r = -0.31) (P < 0.0001). Yield plant^{-1} trend line slope was more negative with SF compared to without SF (Figure 6).

Nashua, Iowa

Soil tests for P were optimum to high in 2011 and low to very low in 2012 (Sawyer et al., 2002). In 2011, in an attempt to promote variability, seeds were planted before Extension recommendations (Elmore, 2011) and subsequently remained in the soil for approximately 29 – 42 days before emerging which resulted in poor emergence and stands. Early-season stand counts were affected by all three main experimental factors: hybrid, seeding rate, and SF in 2011 (Table 5). In 2011, late-season stand counts differed with hybrids, however, not with seeding rates (Table 5). In 2012, as expected late-season stand counts were related to the seeding rates (Table 5). Hybrid 1 averaged more plants·ha^{-1} during late-season stand counts (Table 5).

In 2011 estimated plant biomass CV at V3 among hybrids varied along with both seeding rate and SF (data not shown), however, general trends were unclear. In addition, estimated plant biomass CV at V9 varied among the different hybrids (data not shown). In 2011, increasing seeding rate above 88.9 x 10^3 seeds·ha^{-1} resulted in increased yield plant^{-1} CV (data not shown). In 2011, increasing yield plant^{-1} CV was poorly related to plot grain yield (r = 0.05) (P = 0.66), however, in 2012, increasing yield plant^{-1} CV was negatively correlated to reduced yield (r = -0.34) (P = 0.0036) (Figure 7). Increasing plant spacing standard deviation was poorly correlated (r = 0.02 and -0.04)(P = 0.8508 and P = 0.7664) for

2011 and 2012, respectively, with yield plant^{-1} CV (Data not shown). Yield ha^{-1} was negatively correlated (r = -0.40) with plant spacing standard deviation in 2011(P = 0.0006) but positively correlated (r = 0.26) in 2012 (P = 0.0297) (Figure 8).

Discussion

Plant spacing standard deviation had a negative effect on corn grain yield on an area basis in 2011 at both locations but not in 2012 at Ames (Figures 6 and 10). Corn grain yield per area increased with increasing plant spacing standard deviation in 2012 at Nashua. The response of Nashua in 2012 may have been a result of the drought stress having more of an effect on grain yield than plant spacing standard deviation. The results of 2011 were similar to those of (Nielson, 2001) while the results of 2012 at Ames were similar to those of (Liu et al., 2004b; Liu et al., 2004c). Differences in environment could explain the lack of response in 2012; in that year drought likely caused more stress on plants than stress caused by competition. Under ideal conditions, in a high yield environment, reducing plant spacing standard deviation is likely to increase yield (Nielsen, 2001; Lauer and Rankin, 2004). Plant spacing standard deviation was not correlated to yield plant^{-1} CV, contrary to what we expected (Figures 4 and 9).

Early-season plant-to-plant variability in growth increased with SF at the low seeding rate in 2011; this plant-to-plant variability remained through R2 and was also observed in grain yield variability. Starter fertilizer reduced plant-to-plant variability at the high seeding rate at V6 in 2011, however, this did not continue as a trend into the reproductive stages. The measurable variability in growth due to SF at the low seeding rate and hybrids at increasing seeding rates consistently reflected in grain yield variability at Ames both years.

Starter fertilizer altered the yield of plants emerging at different times. The more negative trend line for grain yield plant^{-1} in response to emergence date associated with SF compared to the no SF treatment shows that late emerging plants were less likely to compete with early emerging plants when SF was applied (Figure 7). Increased growth and development of early-emerging plants increased competitive ability compared to later emerging plants; late emerging plants that did not receive SF were able to compete with early emerging plants more. This tends to agree with the results of (Edmeades and Daynard, 1979; Ford and Hicks, 1992; Lawles et al., 2012; Tollenaar and Wu, 1999) in that later emerging plants were less able to compete with plants that emerged earlier. However, SF enhanced the competitive ability of early-emerging plants. Furthermore, this was different than the results of (Caviglia and Melchiori, 2011) in that dominated plants in their study responded to additional nitrogen; rather, in our study the additional nutrients enhanced the dominant plants.

Variability in growth and plant grain yield induced by SF was not correlated to total grain yield during 2011 when environmental stress was not severe. Variability in growth and plant grain yield had a negative effect on total grain yield in 2012; however, this variability was related to hybrid and seeding rates but not SF. This possibly occurred because of the additional drought stress imposed on plants. Plant-to-plant variability in high- stress situations negatively affects yield, however, under low-stress situations, plant-to-plant variability is not likely to reduce yield. Starter fertilizer may reduce early-season stress in nutrient deficient fields but may not in years where other factors like drought are yield-limiting factors.

Conclusion

Starter fertilizer increased plant-to-plant variability at the low seeding rate in Ames in 2011. Plant-to-plant variability in growth translated into plant-to-plant variability in grain yield both years at Ames. Plant-to-plant variability in growth and grain yield was correlated to a negative effect on yield·ha^{-1} in 2012 – with the additional factor of drought, but not in the less stressful year of 2011. Starter fertilizer enhanced the competitive ability of early-emerging plants compared to late emerging plants (Figure 7). Differential stress associated with environmental conditions during the years likely impacted the yield·ha^{-1} response to plant-to-plant variability. Starter fertilizer may reduce early-season stress in nutrient limited fields, however, stresses later during growth affect yield more and may diminish the effects of reduced early season stress.

Table 1. Accumulated growing degree days (GDDs) after seeding for each sampling stage at Ames, IA and Nashua, IA in 2011 and 2012. Growing degree days C° were calculated using information compiled from Iowa Environmental (IEM, 2013). This table was presented previously in Pierson et al, (2013).

		GDDs after Seeding	
Ames	Stage	2011	2012
	V2	123	153
	V4	250	221
	V6	340	290
	V9	477	498
	V15	670	685
	R2	824	933
Nashua	V3	140	286
	V8	426	605
	R2	844	1053

Table 2. Parameters for biomass equations at each sampling stage during 2011 and 2012 at both locations. Equations were developed using SAS PROC REG correlating plant height and stem diameter to measured plant biomass. This table was presented previously in Pierson et al., (2013a).

	Development Stage	Intercept	Height	Stem Diameter	Stem Diameter^2	R^2
Ames						
2011	V2	-0.08178	0.01142	0.03248	-0.00392	0.57
	V4	0.03097	0.04032	-0.21899	0.02036	0.79
	V6	-0.44809	0.10744	-0.47866	0.02317	0.83
	V9	-9.85963	0.31422	-1.83359	0.07502	0.85
	V15	-8.58485	0.79943	-13.05423	0.43768	0.73
	R2	-97.66933	0.36275	2.76720	0.15903	0.78
2012	V2	-0.06890	0.02365	-0.06910	0.01239	0.80
	V4	-0.34018	0.04848	-0.12082	0.01351	0.91
	V6	0.21454	0.09130	-0.53933	0.03218	0.95
	V9	5.86665	0.78563	-3.60982	0.12962	0.94
	V15	6.97339	2.19451	-14.75962	0.49362	0.84
	R2	-53.36158	1.83900	-9.5239	0.53527	0.89
Nashua						
2011	V3	0.00278	0.01406	-0.06086	0.01084	0.91
	V9	-8.83925	0.96366	-1.70788	0.05394	0.79
	R2	-81.55136	1.20335	-1.17941	0.24236	0.70
2012	V3	-0.21651	0.03116	-0.04909	0.00964	0.86
	V9	-5.57619	0.98030	-3.04556	0.11363	0.91
	R2	-127.02261	0.50032	8.35711	0.15290	0.73

Table 3. Starter fertilizer, seeding rate, and hybrid effects on emergence rate index (ERI) average days to emergence after planting, and early- and late- season populations Ames, IA 2011 and 2012. Data presented in this table was presented previously in Pierson et al., (2013a, 2013b). Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}.

Year	Starter	ERI	Emergence (Days after seeding)	Early-season population	Late-season population
2011	Yes	11.9 a‡	8.42 a	84,300 a	85,200 a
	No	11.9 a	8.41 a	85,600 a	86,800 b
2012	Yes	10.6 a	9.16 a	85,500 a	84,000 a
	No	10.6 a	9.19 a	85,500 a	83,900 a
	Seeding rate (Seeds·ha^{-1})				
2011	74,1 × 10^3	11.9 a	8.45 a	69,700 a	71,300 a
	88.9 × 10^3	11.8 a	8.39 a	85,800 b	86,500 b
	103.7 × 10^3	11.9 a	8.40 a	99,200 c	100,300 c
2012	74.1 × 10^3	10.5 a	9.20 a	70,600 a	70,200 a
	88.9 × 10^3	10.6 a	9.14 a	85,000 b	84,200 b
	103.7 × 10^3	10.6 a	9.19 a	100,900 c	97,500 c
	Hybrid				
2011	1†	11.9 a	8.31 a	85,800 a	85,800 a
	2	11.8 b	8.58 b	84,500 a	87,000 a
	3	11.9 a	8.36 a	84,400 a	85,300 a
2012	1	10.6 ab	9.17 a	86,000 a	85,300 a
	2	10.6 a	9.10 a	86,000 a	83,800 a
	3	10.5 b	9.25 b	84,300 a	82,800 a

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.

‡ Means within the same column and the same year followed by the same letter are not different ($P \leq 0.05$).

Table 4. Average coefficient of variation (CV) of estimated plant biomass at various sampling dates at Ames in 2011 and yield CV. Plant biomass was estimated using models developed by measuring plant height, stem diameter, and biomass of destructively sampled plants (Table 2). Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}.

Seeding rate ha^{-1}	Starter	V2	V4	V6	V9	V15	R2	Yield CV (g plant^{-1})
74.1 x 10^{3}	Yes	26 a†	37 a	35 a	30 ab	31 ab	28 a	21 ab
	No	18 b	23 c	25 b	21 c	19 c	16 b	12 c
88.9 x 10^{3}	Yes	19 ab	28 bc	26 b	23 bc	26 abc	23 ab	21 ab
	No	18 b	27 bc	29 ab	24 bc	23 bc	21 ab	19 cb
103.7 x 10^{3}	Yes	18 b	26 bc	25 b	26 ab	29 ab	27 a	28 a
	No	17 b	30 ab	33 a	32 a	32 a	28 a	28 a
P Diff‡		0.330	0.001	0.003	0.024	0.040	0.088	0.233

† Means within the same column followed by the same letter are not different ($P \leq 0.05$).
‡ *P* Diff is the probability of a difference. $P \leq 0.05$ were considered significant unless otherwise noted.

Table 5. Starter fertilizer, seeding rate, and hybrid effects of early-season populations, and late season populations Nashua, IA 2011 and 2012. Starter fertilizer was 10-34-0 (ammonium polyphosphate) applied at a rate of 104.5 kg·ha^{-1}.

Year	Starter	Early-season Population	Late-season Population
2011	Yes	61,200 b‡	88,700 a
	No	64,200 a	84,500 a
2012	Yes	70,600 a	83,100 a
	No	75,100 a	84,000 a
	Seeding Rate (Seeds·ha^{-1})		
2011	74.1×10^3	52,000 a	86,200 a
	88.9×10^3	63,500 b	88,300 a
	103.7×10^3	72,700 c	85,300 a
2012	74.1×10^3	75,700 a	70,200 a
	88.9×10^3	72,800 a	83,500 b
	103.7×10^3	70,000 a	97,000 c
	Hybrid		
2011	1†	59,600 b	90,300 a
	2	76,500 a	80,200 b
	3	52,000 c	89,400 a
2012	1	70,500 a	85,200 a
	2	74,200 a	83,100 b
	3	73,800 a	82,500 b

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.

‡ Means within the same column followed by the same letter are not different ($P \leq 0.05$).

§ Not all plants had emerged at early-season population counts.

Table 6. Average coefficient of variation (CV) of estimated plant biomass at various sampling dates at Ames in 2012. Plant biomass of 720 "tagged" plants was estimated using models developed by measuring plant height, stem diameter, and biomass of 360 destructively sampled plants per sampling (Table 2).

Hybrid	Seeding Rate	V2	V4	V6	V9	V15	R2	Yield (g plant^{-1})
1†	74.1 x 10^3	28 abc‡	32 abc	40 a	40 abc	41 abc	37 abc	45 bc
	88.9 x 10^3	24 c	23 d	27 b	26 d	29 cd	27 c	38 bc
	103.7 x 10^3	27 abc	28 bcd	34 ab	30 cd	32 bcd	32 bc	39 bc
2	74.1 x 10^3	25 bc	26 cd	33 ab	35 bcd	35 bcd	30 c	47 b
	88.9 x 10^3	32 abc	36 ab	40 a	47 a	49 a	46 a	50 b
	103.7 x 10^3	34 a	38 a	39 a	47 a	51 a	46 a	68 a
3	74.1 x 10^3	26 bc	26 cd	33 ab	31 cd	29 d	28 c	33 c
	88.9 x 10^3	33 ab	33 abc	44 a	43 ab	42 ab	42 ab	46 b
	103.7 x 10^3	25 bc	26 cd	27 b	31 cd	34 bcd	32 bc	41 bc
P Diff§		0.061	0.004	0.005	0.003	0.008	0.013	0.014

† Hybrids 1, 2, and 3 are DuPont Pioneer hybrids P0448XR, P0461XR, and P0463XR, respectively.
‡ Means within the same column followed by the same letter are not different ($P \leq 0.05$).
§ *P* Diff is the probability of a difference. $P \leq 0.05$ were considered significant unless otherwise noted.

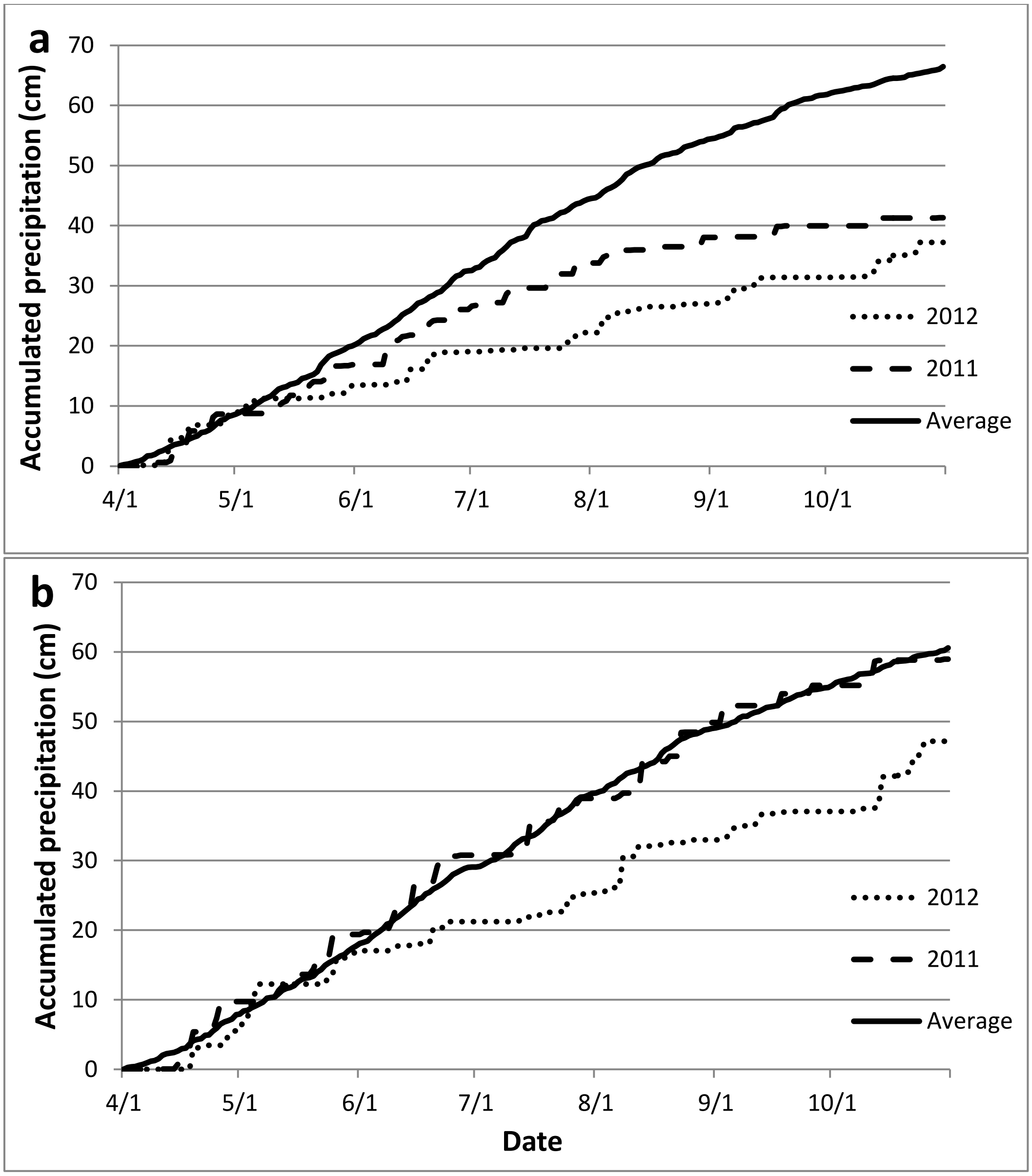

Figure 1. Accumulated precipitation for the growing seasons of 2011, 2012, and the average accumulated precipitation (cm) Ames, IA (**a**) and Nashua, IA (**b**). Data was compiled utilizing Iowa Environmental Mesonet (IEM, 2013). Averages at Ames were based on 26years of data and averages at Nashua were based on 24-years of data.

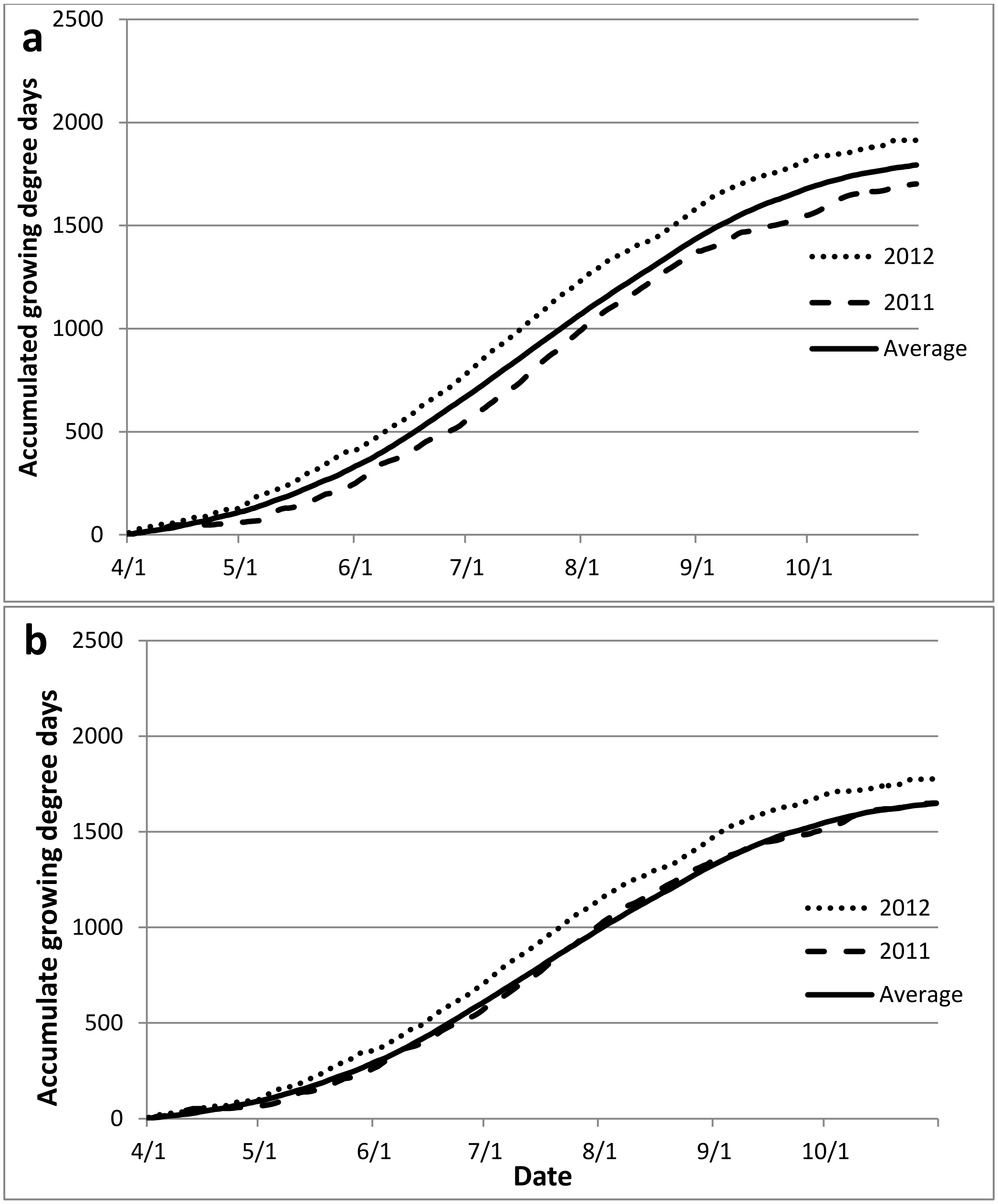

Figure 2. Accumulated growing degree days for the growing seasons of 2011, 2012, and the average accumulated growing degree days (°C). Ames, IA (**a**) and Nashua, IA (**b**). Data was compiled utilizing Iowa Environmental Mesonet (IEM, 2013). Averages at Ames were based on 26years of data and averages at Nashua were based on 24-years of data

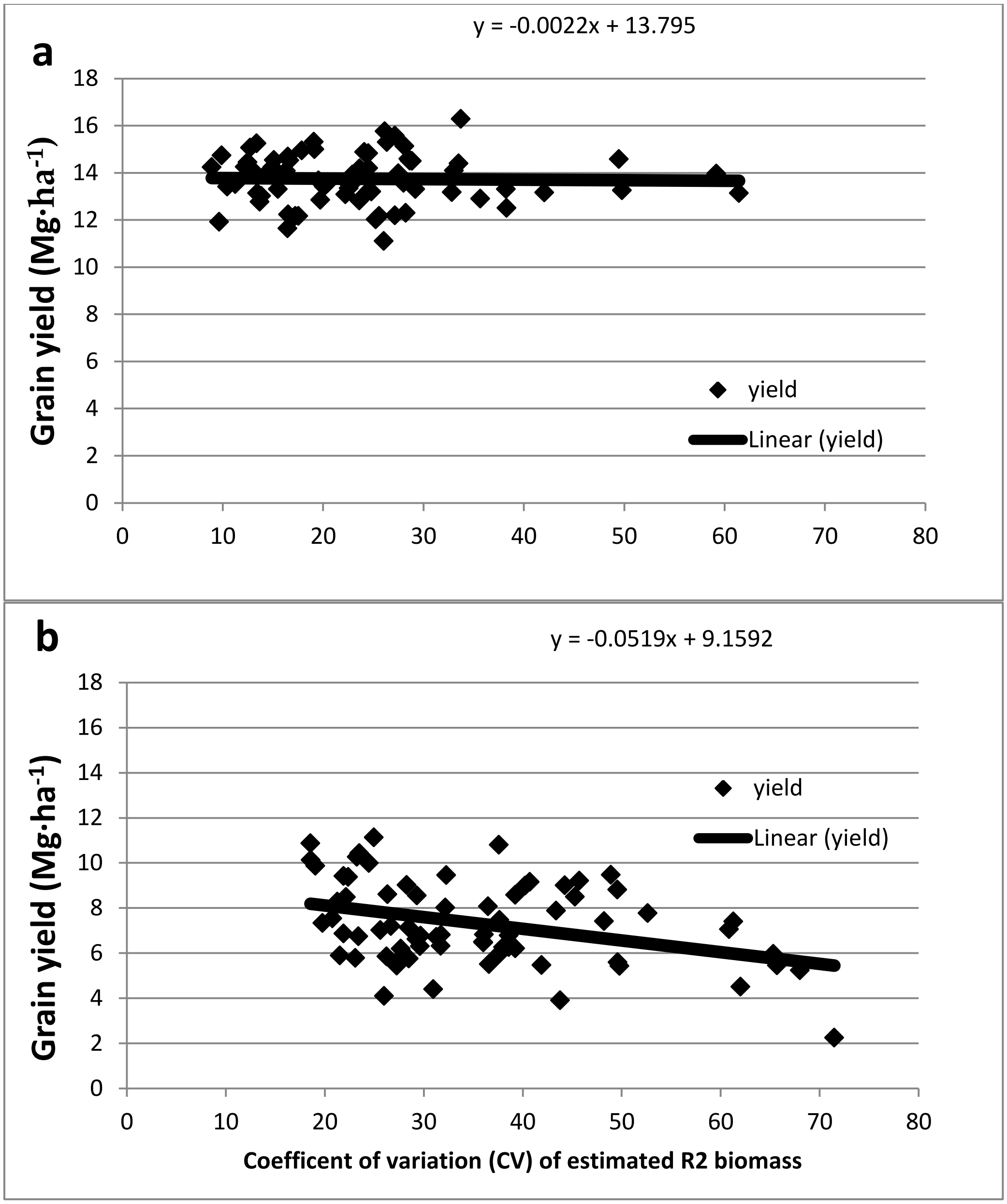

Figure 3. Grain yield (Mg·ha^{-1}) in relation to the coefficient of variation (CV) of estimated plant biomass at R2 for both years. Biomass was estimated using a model to correlate plant height and stem diameter measurements to biomass of destructively sampled plants. Ames, 2011 (**a**) and 2012 (**b**).

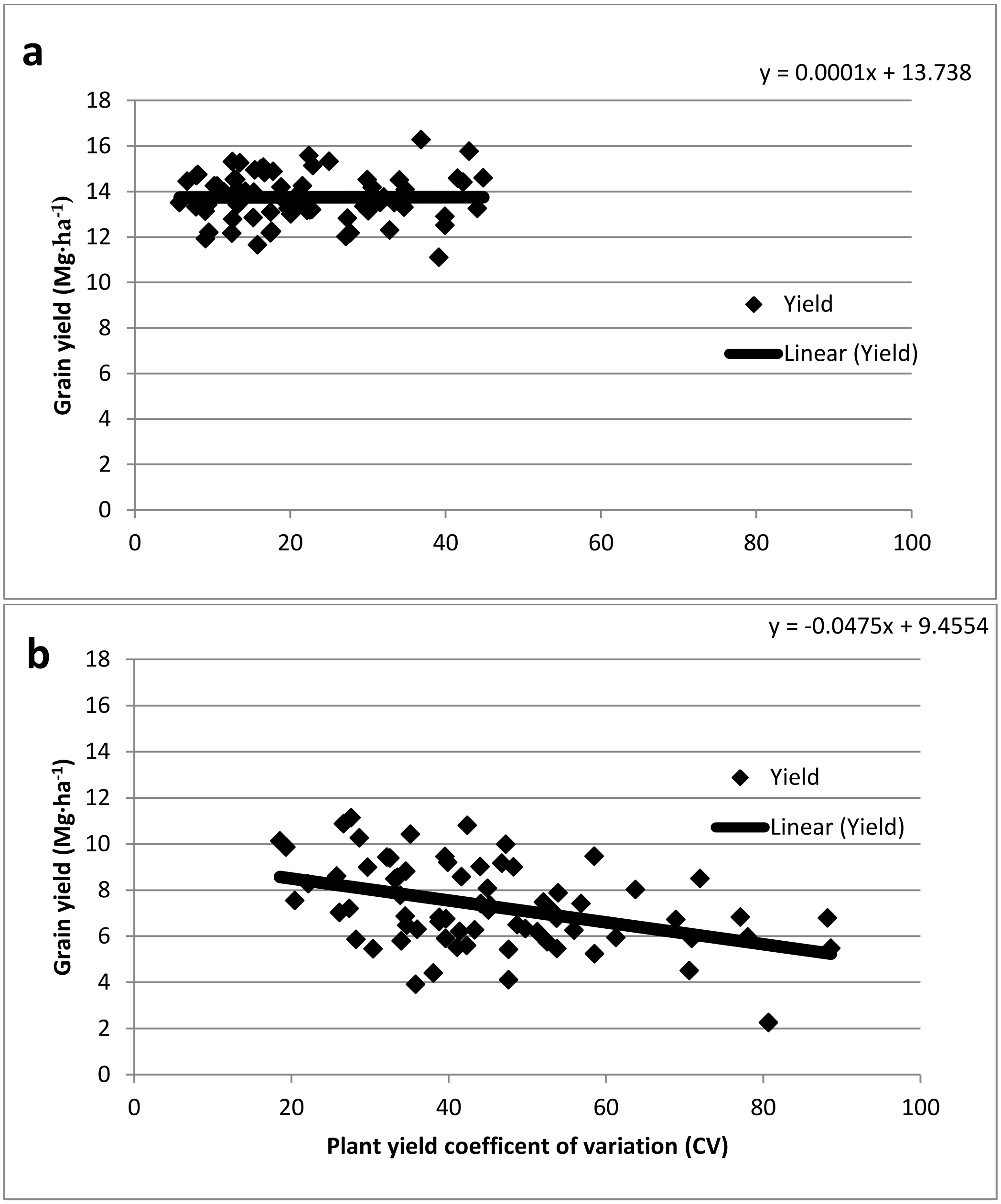

Figure 4. Grain yield ($Mg \cdot ha^{-1}$) in relation to the coefficient of variation of grain yield $plant^{-1}$.

Ames, 2011 (**a**) and 2012 (**b**).

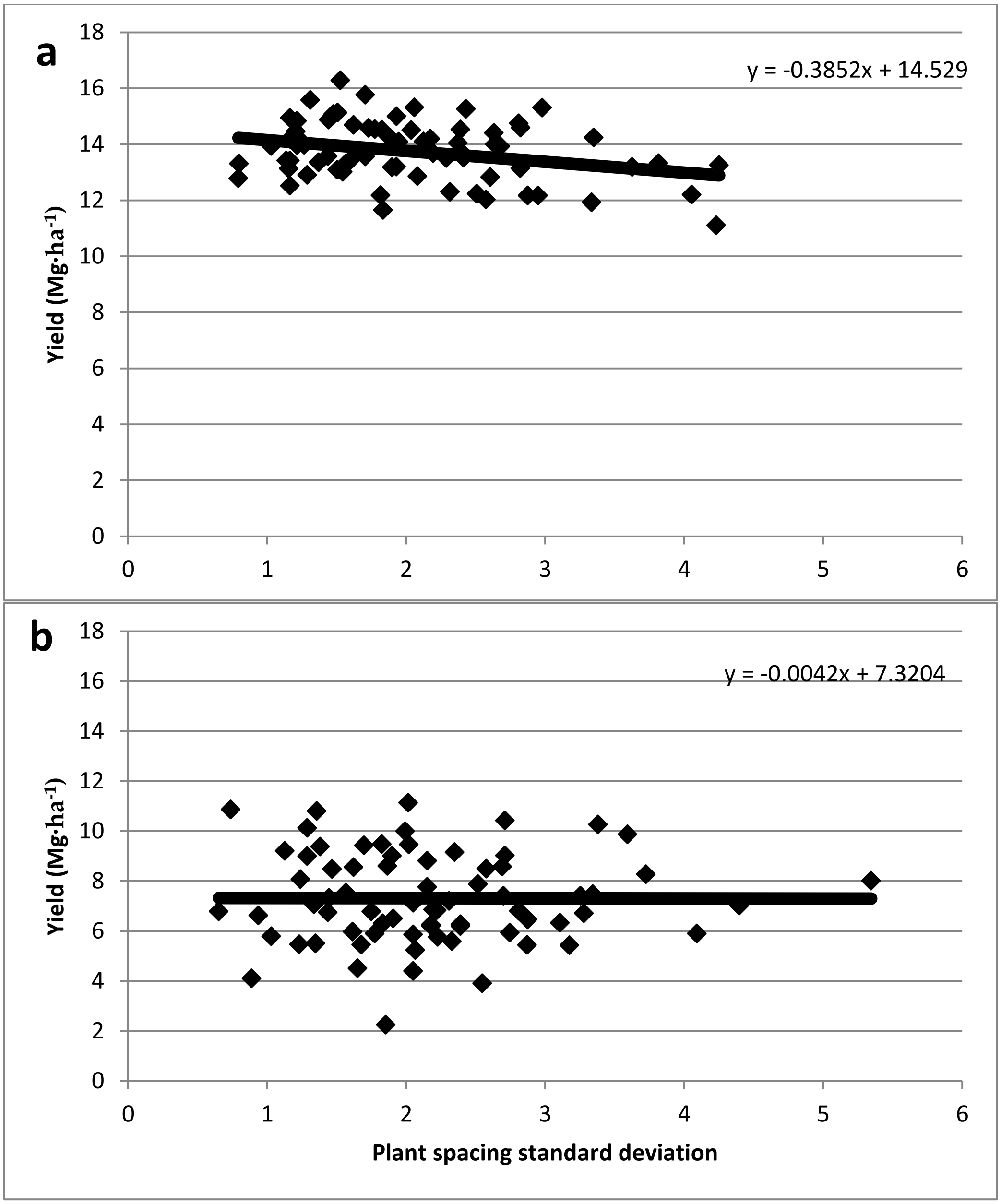

Figure 5. Grain yield (Mg·ha^{-1}) in response to plant spacing standard deviation. Ames, 2011 (**a**) and 2012 (**b**).

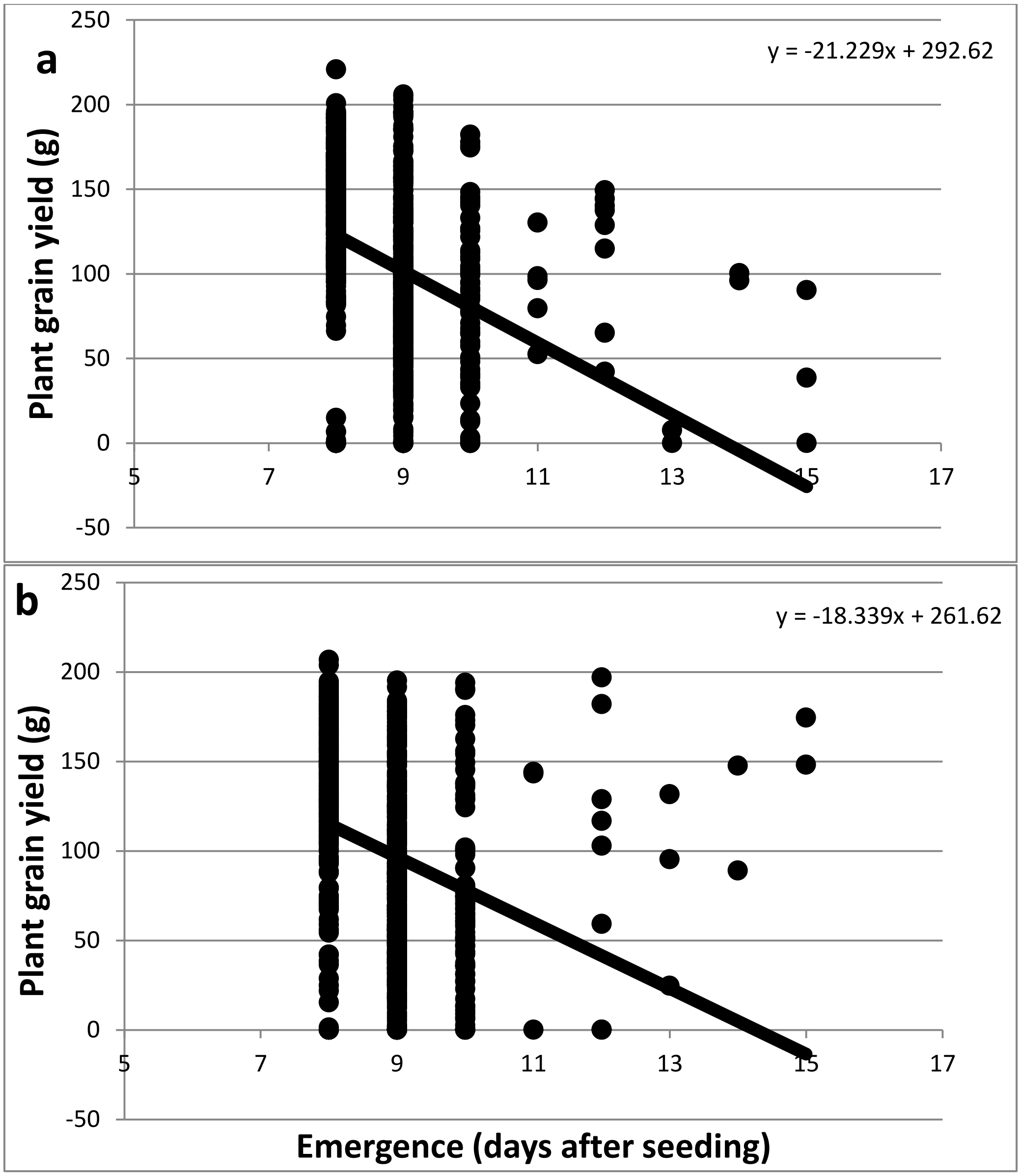

Figure 6. Yield (g·plant^{-1}) response to emergence date (days after planting) separated by the starter (**a**) and no starter (**b**) treatments. Ames, IA 2011 and 2012 combined.

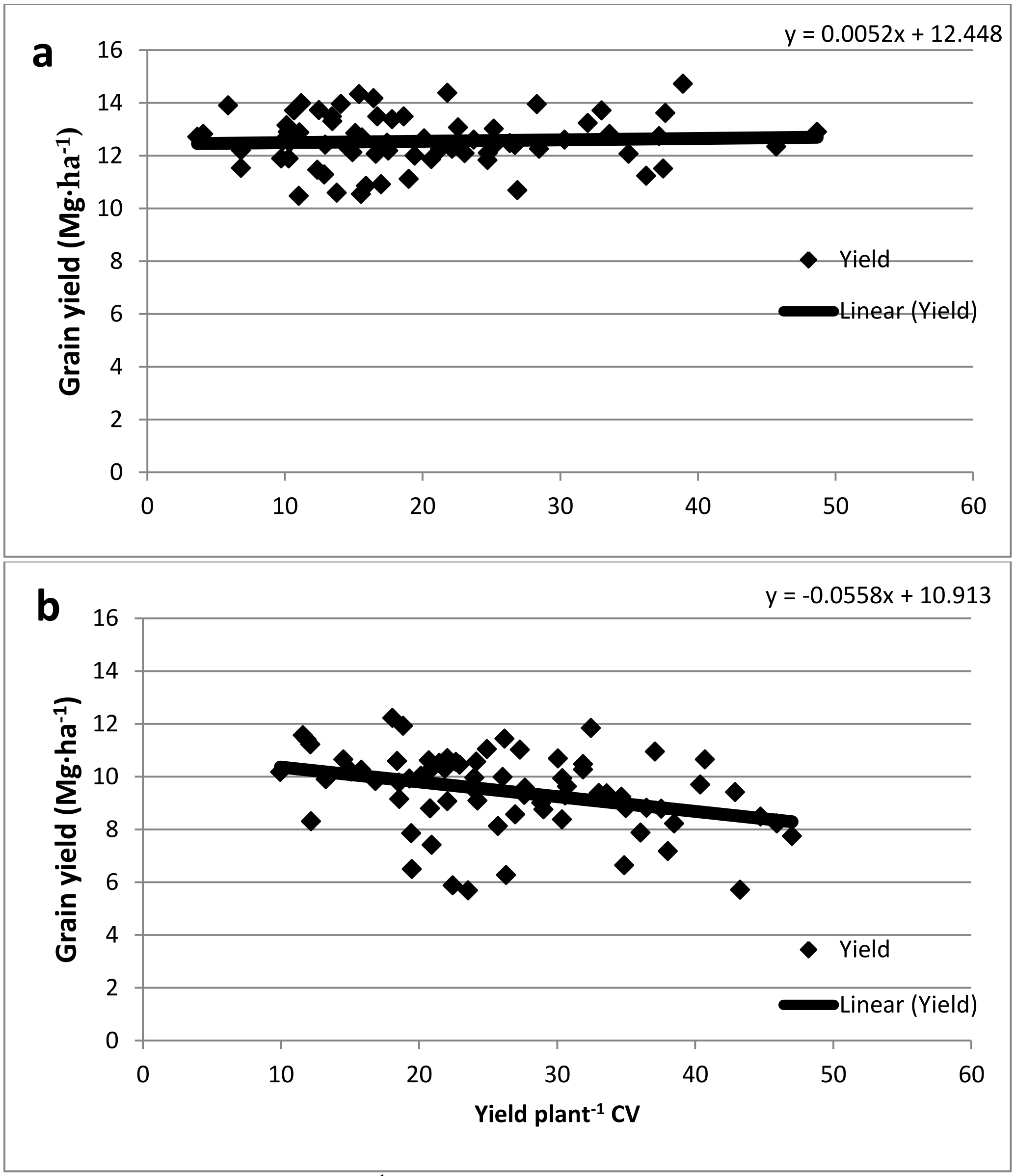

Figure 7. Grain yield (Mg·ha^{-1}) in relation to the coefficient of variation of grain yield plant^{-1}.

Nashua, 2011 (**a**) and 2012 (**b**).

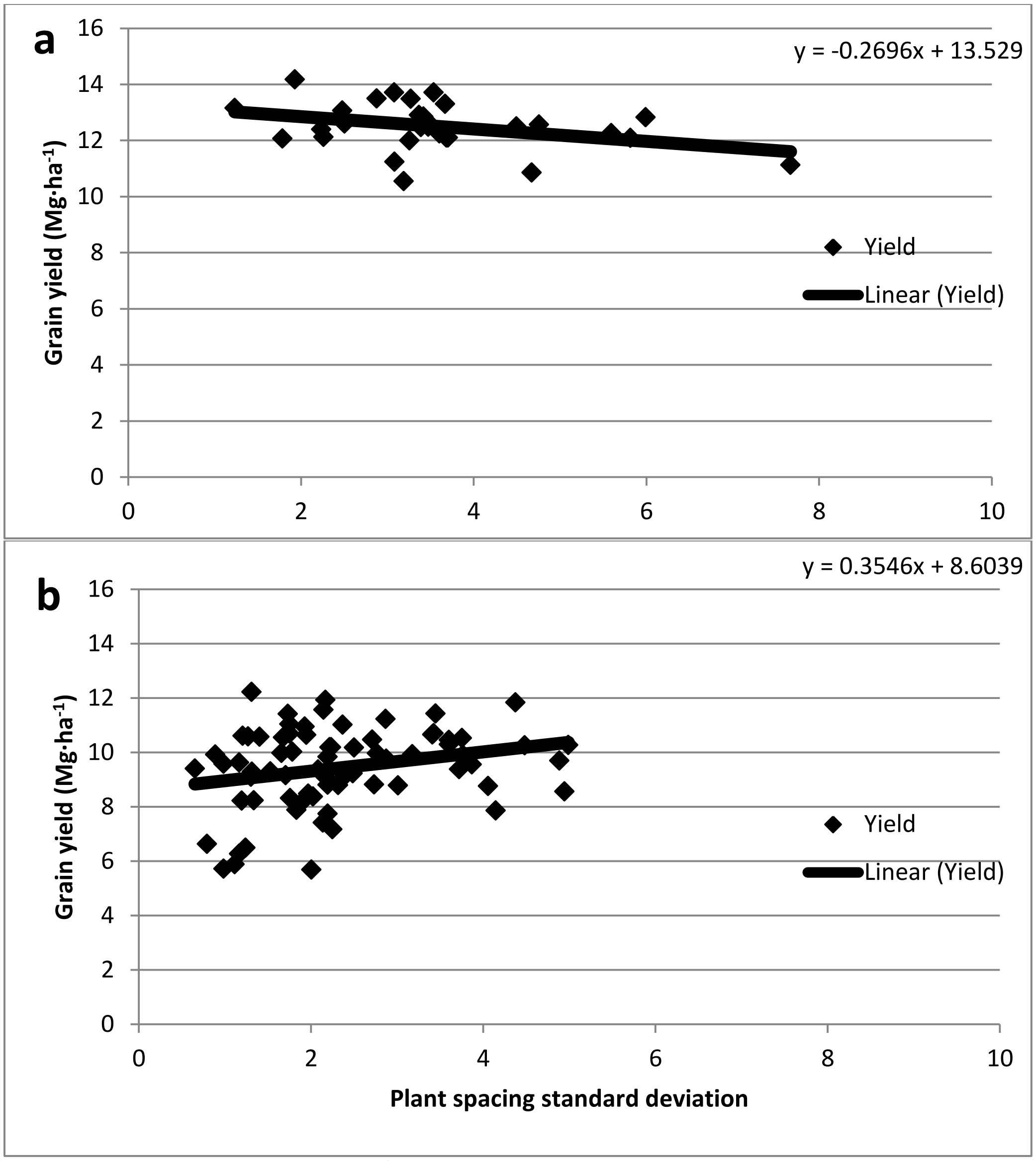

Figure 8. Grain yield (Mg·ha^{-1}) in response to plant spacing standard deviation. Nashua, 2011 (**a**) and 2012 (**b**). One outlier from 2011 (a) was removed from analysis…. 5 standard deviations greater than the mean.

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CHAPTER 5: GENERAL CONCLUSIONS

Starter fertilizer sometimes increased growth and developmental rate of corn. Final plant size and grain yield increased in 2012 with starter fertilizer; however, it did not in 2011. This was likely associated with low fertility in 2012 and a fertilizer response, rather than a true starter fertilizer response in that the yield response was due to lack of fertility rather than an increase in early-season growth. The cost of the starter fertilizer applied at Ames is approximately \$27 acre^{-1} and approximately \$30.75 acre^{-1} at Nashua. The lack of response in 2011 would cost farmers the cost of fertilizer; however, yield responses in 2012 would be profitable. Yield response to starter fertilizer was 12.5 bu·ac^{-1} at Ames and 14.1 bu·ac^{-1}. With an average price of \$7.02 bushel^{-1} (USDA-NASS), starter fertilizer would have returned \$60.75 ac^{-1} at Ames and \$68.23 ac^{-1}; however, the yield response was likely due to low fertility and may have been remediated with broadcast fertilizer for farmers without capability to apply starter fertilizer.

While starter fertilizer did not interact with hybrids in Chapter 2 with estimated plant biomass, Chapter 3 was based on destructively sampled plants and hybrids did respond differently to starter fertilizer. The hybrid response to starter fertilizer in early-season was observed for the untagged plants at the V4 sampling in 2011; however, it did not occur at the same sampling for the tagged plants in the research presented in Chapter 2. Furthermore, the response of hybrid to starter fertilizer did not occur in grain yield. Therefore, the importance of this hybrid response to starter fertilizer is not likely important to farmers. More research regarding the effect of starter fertilizer on root growth could be performed to understand if starter fertilizer increases the root similarly to the shoot in that starter fertilizer generally does not increase final plant biomass unless fertility is limiting. However, root studies in fields, performed at maximum vegetative growth are difficult due to excavation at the depth of rooting.

Starter fertilizer increased plant-to-plant variability at the low seeding rate in 2011, reduced variability at the high seeding rate at V6, however, did not affect variability in 2012. The increased variability in growth at the low seeding rate in 2011 did carry over to variability in grain yield per plant. Variability in grain yield per plant was not strongly correlated with yield loss in 2011; however, it was negatively correlated to yield in 2012. Variability in grain yield per plant in 2012 was likely associated to hybrid differences in tolerance to crowding and drought stress.

Based on the data presented in this thesis, starter fertilizer may increase plant-to-plant variability at seeding rates that are considered below optimal for maximum grain yield in Iowa. The variability induced by starter fertilizer at the low seeding rate was not correlated to yield loss and in most farmer fields would not affect yield. Some farmers think that starter fertilizer can reduce plant-to-plant variability in growth and enhance stands. However, more focus on planting and planter maintenance is likely more important to reduce plant-to-plant variability within farmer fields. Focusing on adjusting down pressure and pressure on closing wheels, along with planting at the recommended speed so that seeds are placed at uniform depths, are likely more important for uniform emergence and growth. Also, the addition of row cleaners may remove residue and promote more uniform emergence.

Although starter fertilizer did not reduce variability and maximize yields in our study, it did increase growth and developmental rate of corn. Starter fertilizer could be used as a management tool for farmers to increase growth rate of corn when planting corn late so that corn reaches maturity before a killing freeze. Farmers could also plant short season hybrids with SF to attempt to harvest and sell their crop to take advantage of old crop prices. Starter fertilizer could also be used early in the season to vary the development of corn to spread risk of stress during critical grain fill periods. Farmers also pay drying costs due to harvest moisture above 155 $g \cdot kg^{-1}$ and as harvest moisture increases, grain storability decreases. Starter fertilizer decreased grain moisture at harvest and could be used as a tool to extend the temporal period for grain harvest by 1 to 2 days when applied to early-planted fields.

Potential areas of research regarding starter fertilizer with corn include grain quality and effects on disease development. Root strength ratings by the seed industry are based on standability after winds. The ratings of hybrids used in this study did not indicate hybrids that would respond to SF. Most research, including this study, suggests that hybrids in the Midwest do not respond differently to SF, however, more hybrids would be required to conclude that root strength ratings should not be used as a tool to recommend SF.

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APPENDIX

Table 1. Emergence, population, and spacing data for Ames, IA 2011 and 2012.

Year	Hybrid	Seeding rate	SF†	Emergence (days after seeding)	ERI‡	Early-season population (plants·ha^{-1})	Late-season population (plants·ha^{-1})	Spacing deviation	Average spacing
2011	1	74,100	Yes	8.175	0.1205	71,321	72,865	2.0186	7.5
			No	8.5721	0.118	71,939	72,865	1.566	7.1326
		88,900	Yes	8.525	0.1181	86,759	85,524	1.7424	6.2254
			No	8.075	0.119	87,685	87,376	2.0085	5.8542
		103,700	Yes	8.325	0.1205	96,021	95,713	1.6287	5.1875
			No	8.1779	0.1194	101,270	100,344	2.1888	5.7708
	2	74,100	Yes	8.6	0.117	69,160	70,086	3.3839	7.7803
			No	8.575	0.1178	69,469	73,483	3.0816	8.1667
		88,900	Yes	8.475	0.1178	83,671	86,141	2.4755	6.3542
			No	8.5446	0.1177	86,141	87,685	1.4519	5.8163
		103,700	Yes	8.7	0.1165	100,344	103,431	1.774	5.0625
			No	8.575	0.1187	98,183	100,961	1.7646	5.2708
	3	74,100	Yes	8.475	0.1203	66,690	67,616	1.9804	7.5208
			No	8.3	0.1197	69,469	70,704	1.6213	7.1099
		88,900	Yes	8.2	0.1191	83,980	83,980	2.4126	6.5455
			No	8.55	0.1183	86,759	87,994	2.1066	6.3333
		103,700	Yes	8.325	0.1192	100,344	101,579	1.749	5.3958
			No	8.3	0.1195	99,109	99,726	1.8682	5.3712
2012	1	74,100	Yes	9.275	0.1045	71,939	70,704	2.128	7.2292
			No	9.175	0.1053	69,778	69,778	2.3196	7.1402
		88,900	Yes	9.025	0.1068	87,376	86,141	1.3741	5.8333
			No	9.15	0.1052	87,068	86,141	2.1317	6.1512
		103,700	Yes	9.175	0.1057	100,344	98,800	2.5114	5.3125
			No	9.2	0.1079	100,035	100,035	1.7687	5.3542
	2	74,100	Yes	9.05	0.1061	70,086	71,321	3.4386	8.2484
			No	9.175	0.1055	71,630	69,778	3.1318	7.3523
		88,900	Yes	9.075	0.1052	85,215	84,598	1.7665	6.375
			No	9.075	0.1075	84,289	82,745	2.0109	6.3542
		103,700	Yes	9.125	0.1076	101,270	97,874	1.9107	5.6042
			No	9.125	0.1064	103,740	96,639	1.6534	5.0946
	3	74,100	Yes	9.275	0.1027	70,395	71,321	2.781	7.8958
			No	9.225	0.105	69,469	68,234	2.4179	7.7083
		88,900	Yes	9.25	0.1059	83,671	81,510	2.2834	6.5
			No	9.25	0.1039	82,128	83,980	2.0328	6.6042
		103,700	Yes	9.175	0.1055	99,109	94,169	1.7341	5.4375
			No	9.35	0.1039	100,961	97,565	1.7306	5.3333

†SF = Starter fertilizer
‡ERI = Emergence rate index

Table 2. Average heights for tagged plants at Ames, IA in 2011 and 2012. Heights were measured in cm.

Year	Hybrid	Seeding rate	Starter fertilizer	Height V2	Height V4	Height V6	Height V9	Height V15	Height R2
2011	1	74,100	Yes	10.63	33.54	60.08	120.17	208.53	227.84
			No	9.98	29.51	53.72	114.08	206.01	231.55
		88,900	Yes	10.52	32.04	57.41	119.31	206.52	226.89
			No	10.73	30.12	55.82	118.97	207.9	227.77
		103,700	Yes	11.09	35.09	62.43	123.51	203.58	220.34
			No	11	31.19	56.42	116.27	203.13	224.89
	2	74,100	Yes	9.73	31.78	55.2	113.47	208.41	229.3
			No	9.66	29.51	52.07	107.09	209.39	235.58
		88,900	Yes	9.81	31.1	53.64	110.01	203.71	227.58
			No	9.53	27.41	48.59	105.93	198.67	228.38
		103,700	Yes	9.82	32.14	55.48	114.65	203.71	227.77
			No	9.85	29.18	52.18	107.47	199.77	226.25
	3	74,100	Yes	10.59	33	58.47	115.63	208.03	222.95
			No	10.79	32.59	58.52	119.7	217.87	233.74
		88,900	Yes	11.26	34.22	61.3	120.78	216.57	231.9
			No	10.79	30.55	55.09	114.03	209.36	229.96
		103,700	Yes	10.85	32.93	57.56	116.21	204.34	221.11
			No	10.38	27.86	49.74	103.72	193.4	212.56
2012	1	74,100	Yes	17.53	29.04	45.86	121.16	196.21	222.57
			No	17.43	27.85	43.66	111.41	178.94	212.15
		88,900	Yes	18.95	32.15	49.44	125.38	193.93	215.27
			No	17.56	29.15	44.39	117.99	183.68	209.22
		103,700	Yes	19.41	32.41	49.33	124.3	189.36	211.65
			No	17.68	28.79	44.65	117.73	181.67	207.33
	2	74,100	Yes	18.18	29.99	45.79	119.32	198.12	226.19
			No	16.39	27.13	41.13	106.93	182.53	219.46
		88,900	Yes	17.64	28.63	44.26	112.08	186.63	213.61
			No	15.65	26.64	41.39	105.51	177.67	210.38
		103,700	Yes	16.4	27.33	42.21	104.84	173.55	205.93
			No	16.78	26.85	41.76	101.76	166.5	198.88
	3	74,100	Yes	17.76	29.96	47.2	126.4	203.84	221.68
			No	16.29	27.64	42.9	118.27	198.31	223.96
		88,900	Yes	16.76	26.79	39.74	110.3	182.69	206.31
			No	16.04	26.11	38.93	104.84	181.29	213.87
		103,700	Yes	19.01	31.66	49.79	128.78	198.63	215.46
			No	15.94	26.23	40.09	105.41	172.97	200.47

Table 3. Average stem diameter for tagged plants at Ames, IA in 2011 and 2012. Stem diameters were measured in mm using an electronic caliper.

Year	Hybrid	Seeding rate	Starter fertilizer	Stem diameter V2	Stem diameter V4	Stem diameter V6	Stem diameter V9	Stem diameter V15	Stem diameter R2
2011	1	74,100	Yes	2.57	8.16	16.1	23.72	22.97	21.95
			No	2.5	6.98	14.39	23.27	22.55	21.55
		88,900	Yes	2.53	7.46	15.06	22.34	21.83	19.19
			No	2.5	7.21	14.64	22.6	21.88	20.49
		103,700	Yes	2.41	7.92	14.13	22.57	21.4	18.67
			No	2.59	7.34	14.76	22.66	22.05	20.69
	2	74,100	Yes	2.43	7.8	15.9	24.82	23.49	22.15
			No	2.5	6.93	14.48	25.5	24.21	22.77
		88,900	Yes	2.52	7.41	15.07	23.51	22.41	20.85
			No	2.3	6.21	12.6	22.24	21.5	20.17
		103,700	Yes	2.4	7.15	14.72	22.54	21.21	19.63
			No	2.5	6.3	13.5	22.32	21.37	19.53
	3	74,100	Yes	2.35	7.82	15.17	23.62	22.33	21.86
			No	2.43	8.08	14.48	24.18	23.1	22.41
		88,900	Yes	2.47	7.96	15.65	23.08	22.06	19.68
			No	2.39	7.27	14.6	22.73	22.47	20.9
		103,700	Yes	2.51	7.67	15.08	22.17	20.7	19.46
			No	2.14	6.2	12.98	20.26	19.02	18.58
2012	1	74,100	Yes	4.28	7.61	11.77	20.91	22.32	20.26
			No	4.18	7.23	10.91	20.87	21.95	20.33
		88,900	Yes	4.59	8.16	12.43	21.37	20.71	18.93
			No	4.3	7.37	11.08	20.72	20.62	19
		103,700	Yes	4.77	8.12	11.84	20.12	19.67	18.17
			No	4.37	7.13	10.55	19.64	19.04	17.42
	2	74,100	Yes	4.65	8.54	12.42	23.51	24.09	21.46
			No	4.15	6.73	10.66	21.98	23	20.87
		88,900	Yes	4.49	7.74	11.36	21.39	21.57	19.43
			No	3.97	6.79	10.48	20.12	20.93	18.47
		103,700	Yes	4	6.76	10.09	19.39	19.96	17.28
			No	4.13	6.65	10.01	19.51	19.94	17.22
	3	74,100	Yes	4.25	7.95	11.95	22.84	22.42	21.05
			No	3.66	6.83	10.6	22.3	22.53	21
		88,900	Yes	3.97	6.59	10.1	19.52	19.69	18.65
			No	3.93	6.32	10.26	20.12	21.04	19.02
		103,700	Yes	4.27	7.94	11.53	20.89	20.7	18.85
			No	3.57	6.22	9.65	19.06	19.31	17.29

Table 4. Average vegetative growth stage of corn at sampling dates. Plants were vegetatively staged to 0.25 accuracy using a modified version of the leaf-collar method (Abendroth et al., 2011).

Year	Hybrid	Seeding rate	Starter fertilizer	V4 sampling stage	V6 sampling stage	V9 sampling stage	V15 sampling stage
2011	1	74,100	Yes	4.54	6.43	9.13	15.78
			No	4.39	6.25	8.94	14.84
		88,900	Yes	4.41	6.37	9.02	15.19
			No	4.36	6.19	8.86	15
		103,700	Yes	4.53	6.33	9.09	15.44
			No	4.42	6.3	8.85	15.01
	2	74,100	Yes	4.54	6.43	9.3	15.99
			No	4.34	6.28	9.03	15.81
		88,900	Yes	4.46	6.26	9.11	15.48
			No	4.18	6.07	8.66	14.85
		103,700	Yes	4.5	6.31	9.04	15.4
			No	4.31	6.2	8.81	15.04
	3	74,100	Yes	4.33	6.29	8.78	16.01
			No	4.38	6.31	8.94	16.04
		88,900	Yes	4.46	6.31	8.76	15.76
			No	4.24	6.16	8.56	15.4
		103,700	Yes	4.34	6.27	8.73	15.19
			No	4.13	5.99	8.28	14.77
2012	1	74,100	Yes	4.08	5.44	9.03	14.83
			No	3.92	5.39	8.87	14.11
		88,900	Yes	4.11	5.5	9	14.78
			No	3.94	5.42	8.78	14.22
		103,700	Yes	4.12	5.42	8.99	14.66
			No	3.94	5.25	8.7	13.97
	2	74,100	Yes	4.21	5.51	9.28	15.44
			No	3.83	5.37	8.94	14.5
		88,900	Yes	4.08	5.44	9.03	15.03
			No	3.89	5.32	8.68	13.99
		103,700	Yes	3.89	5.34	8.79	14.07
			No	3.87	5.27	8.65	13.42
	3	74,100	Yes	4.03	5.43	8.95	15.53
			No	3.64	5.3	8.55	14.53
		88,900	Yes	3.65	5.16	8.43	14.09
			No	3.65	5.14	8.43	13.81
		103,700	Yes	3.98	5.44	8.76	15.16
			No	3.64	5.21	8.37	13.51

Table 5. Starter fertilizer, seeding rate, and hybrid effects on average estimated biomass across biomass samplings at Ames, IA. Biomass was estimated using models developed through destructive sampling of 360 plants per sampling date utilizing height and stem diameter measurements that were then correlated to biomass.

				Estimated biomass (g·plant^{-1})					
Year	Hybrid	Seeding rate	Starter fertilizer	V2	V4	V6	V9	V15	R2
2011	1	74,100	Yes	0.1	1.02	4.57	2.758	93.81	124
			No	0.09	0.71	3.32	24.33	89.08	120.45
		88,900	Yes	0.09	0.86	3.88	24.46	82.43	97.81
			No	0.1	0.76	3.63	24.88	84.27	109.43
		103,700	Yes	0.1	10.3	4.35	26.22	77.67	90.82
			No	0.1	0.8	3.72	24.03	81.58	109.96
	2	74,100	Yes	0.08	0.91	3.92	27.41	97.76	126.71
			No	0.08	0.72	3.16	26.42	102.04	134.11
		88,900	Yes	0.09	0.81	3.49	23.96	85.91	113.18
			No	0.08	0.58	2.55	20.13	73.93	106.45
		103,700	Yes	0.09	0.84	3.58	23.47	77.5	101.91
			No	0.09	0.69	3.06	20.95	76.06	100.31
	3	74,100	Yes	0.09	0.92	4.07	25.95	89.85	121.89
			No	0.09	0.93	3.96	27.59	100.23	129.64
		88,900	Yes	0.1	0.99	4.44	27.65	90.76	103.73
			No	0.1	0.79	3.62	23.7	89.37	114.02
		103,700	Yes	0.1	0.91	3.9	23.84	75.99	97.91
			No	0.09	0.61	2.72	17.34	60.2	87.32
2012	1	74,100	Yes	0.29	0.97	2.65	27.74	97.42	140.01
			No	0.28	0.88	2.38	23.42	82.51	135.01
		88,900	Yes	0.33	1.16	3.12	27.66	85.32	118.33
			No	0.28	0.94	2.34	23.94	74.56	113.2
		103,700	Yes	0.35	1.17	2.97	25.69	77.47	108.56
			No	0.3	0.92	2.32	22.39	66.43	96.75
	2	74,100	Yes	0.32	1.09	2.75	30.72	113.998	158.26
			No	0.25	0.8	2.05	24.01	94.2	145.3
		88,900	Yes	0.3	0.96	2.48	24.52	87.73	126.67
			No	0.23	0.81	2.1	21.07	78.85	117.01
		103,700	Yes	0.25	0.83	2.1	18.69	66.74	97.99
			No	0.26	0.81	2.09	18.95	63.76	94.02
	3	74,100	Yes	0.29	1.03	2.75	31.43	104.16	148.98
			No	0.24	0.83	2.14	27.58	100.08	149.44
		88,900	Yes	0.26	0.8	1.9	21.14	74.84	113.82
			No	0.24	0.72	1.8	19.54	75.62	118.49
		103,700	Yes	0.32	1.11	2.9	27.83	88.95	116.84
			No	0.22	0.72	1.72	17.84	60.01	91.4

Table 6. Hybrid, seeding rate, and starter fertilizer effects on estimated biomass coefficient of variation at Ames, IA in 2011 and 2012.

				Estimated biomass coefficient of variation (CV)					
Year	Hybrid	Seeding rate	Starter fertilizer	V2	V4	V6	V9	V15	R2
2011	1	74,100	Yes	23.7	35.8	34.1	27.7	26.5	25.4
			No	21	24.4	27.4	22	17.4	15.2
		88,900	Yes	19.8	30.5	27.4	20.8	26	25.2
			No	15	24.5	25.2	20.1	19.8	19.7
		103,700	Yes	20.4	26.8	23.9	19.8	25.3	24.3
			No	12.2	22.4	26.1	22.2	22.2	18.8
	2	74,100	Yes	29	44.7	40.1	35.8	36.7	28
			No	20.3	24.7	26.5	23	22	17.4
		88,900	Yes	21.4	31.9	28.5	32.4	35.4	25.8
			No	21.8	29	34.2	23.5	25	21.3
		103,700	Yes	21.4	26.9	27.3	26	29.3	27.3
			No	14.5	31.4	33.7	31.6	36.6	28.4
	3	74,100	Yes	26.4	29.7	29.5	27.5	29.9	30.8
			No	11.8	19.7	20.8	17.5	17.2	15.6
		88,900	Yes	16.6	22.2	20.5	15.9	16	16.6
			No	16.1	26.9	26.1	27.3	25.4	22
		103,700	Yes	12.5	24.8	24.5	31.5	31.7	29.4
			No	23.4	37.2	38	42.8	37.7	37.3
2012	1	74,100	Yes	24.6	32.2	38.9	36.3	33.5	33.8
			No	31.1	32	40.8	44.3	48.4	39.1
		88,900	Yes	21.1	22.2	22.7	26	29.5	29
			No	27.7	23.3	30.8	25.1	29	25.9
		103,700	Yes	27.1	28.4	35.1	29.5	31.8	31.7
			No	26.3	27.8	33.3	30.9	32.9	32.4
	2	74,100	Yes	23.8	24.6	28.4	27.4	30.1	28.2
			No	25.8	26.7	37	42.4	39.6	31.5
		88,900	Yes	27.1	33.8	36.9	40.3	43.6	40.8
			No	36.9	38.8	42.4	52.8	54.3	51.5
		103,700	Yes	32.2	36.2	40.5	45.5	47.9	43.9
			No	36.6	40	38.3	48.1	54.6	48.9
	3	74,100	Yes	26.9	28.4	32.6	28.8	29	30.5
			No	24.2	23.7	33.2	32.1	28.9	26
		88,900	Yes	37.4	43.6	54.2	49.2	47.2	51.8
			No	27.8	21.7	33.1	36.5	37.3	32
		103,700	Yes	20.6	24.6	23.1	24.7	29.4	28.8
			No	30.2	26.4	30.1	36.4	39.5	35.3

Table 7. Hybrid, seeding rate, and starter fertilizer effects on grain yield and moisture at Ames, IA in 2011 and 2012.

Year	Hybrid	Seeding rate	Starter fertilizer	Grain yield (Mg·ha^{-1})	Grain moisture (kg·g^{-1})
2011	1	74,100	Yes	13.6403	15.45
			No	13.82988	15.41
		88,900	Yes	14.02197	15.62
			No	14.09542	15.42
		103,700	Yes	14.88261	15.57
			No	13.82298	15.66
	2	74,100	Yes	13.21281	15.07
			No	13.70998	15.25
		88,900	Yes	13.5838	14.95
			No	13.87068	15.07
		103,700	Yes	13.58569	15.04
			No	13.87194	15.29
	3	74,100	Yes	12.80226	15.38
			No	13.47772	15.61
		88,900	Yes	13.46202	15.6
			No	12.8801	15.54
		103,700	Yes	14.16133	15.42
			No	14.43252	15.46
2012	1	74,100	Yes	7.870056	17.08
			No	7.448839	17.3
		88,900	Yes	8.057125	17.17
			No	6.978029	17.75
		103,700	Yes	7.418707	17.32
			No	6.856874	17.83
	2	74,100	Yes	7.694915	17.59
			No	6.699309	18.77
		88,900	Yes	7.131199	17.92
			No	6.561833	17.63
		103,700	Yes	5.439422	18.94
			No	4.419335	19.25
	3	74,100	Yes	9.041431	17.35
			No	8.800377	17.82
		88,900	Yes	8.408663	18.01
			No	8.161331	18.81
		103,700	Yes	8.26742	17.61
			No	6.349655	18.38

Table 8. Hybrid, seeding rate, and starter fertilizer effects on grain yield components at Ames, IA in 2011 and 2012.

Year	Hybrid	Seeding rate	Starter fertilizer	Kernel rows per ear	Kernel number	Plant Yield (g plant^{-1})	Moisture (g·kg)$^{-1}$	Yield CV
2011	1	74,100	Yes	15.48	528.1	159.09	22.23	23.4
			No	15.23	511.95	150.74	23.58	11.6
		88,900	Yes	15.13	445	129.87	22.77	15.8
			No	15.5	452.3	131.73	24.29	18.4
		103,700	Yes	15.05	415.28	116.13	22.25	20.7
			No	14.99	418.77	116.37	23.95	19.9
	2	74,100	Yes	16.9	548.37	158.52	22.25	18.1
			No	16.8	540.53	157.67	21.75	12.8
		88,900	Yes	16.3	478.75	129.79	22.14	27.1
			No	16.79	451.6	119.44	24.04	17.5
		103,700	Yes	15.79	404.7	107.7	23.01	36.5
			No	16.08	416.85	112.07	25.31	29.6
	3	74,100	Yes	14.73	525.1	152.19	21.1	21.6
			No	15.8	569.85	164.57	23.31	12.2
		88,900	Yes	15.45	507.37	142.92	22.19	19.3
			No	15.74	518.17	145.26	23.64	21.6
		103,700	Yes	14.2	420.15	115.34	22.36	27.4
			No	13.84	371.17	101.14	22.83	34.1
2012	1	74,100	Yes	14.4	362.97	97.57	15.87	40.7
			No	12.78	331.92	88.9	17.44	49
		88,900	Yes	13.08	286.1	74.36	15.66	34.4
			No	11.33	219.7	58.36	17.21	42.5
		103,700	Yes	11.75	243.03	63.6	15.75	37.7
			No	11.88	238.25	62.01	18.1	40.3
	2	74,100	Yes	12.68	328.95	92.06	19.35	50.5
			No	11.38	280.57	75.32	21.47	43.5
		88,900	Yes	10.98	257.05	70.44	18.39	41.8
			No	9	201.03	55.06	20.86	57.2
		103,700	Yes	9.23	191.65	46.72	22.87	66.5
			No	7.25	147.67	33.85	25.21	69
	3	74,100	Yes	14.33	445.78	115.8	16.19	33.7
			No	14.65	424.65	101.94	16.43	31.7
		88,900	Yes	12.68	333.72	79.5	18.04	46.2
			No	13.38	314.72	74.89	17.72	45.2
		103,700	Yes	13.33	308.32	69	16.54	36.9
			No	10.8	228.95	49.12	17.35	45.3

Table 9. Hybrid, seeding rate, and starter fertilizer effects on time to silking, anthesis, and anthesis-silking-interval (ASI) at Ames, IA in 2011 and 2012.

Year	Hybrid	Seeding rate	Starter fertilizer	Days from planting to silk	Days from planting to pollen shed	ASI
2011	1	74,100	Yes	74.2	74.9	0.725
			No	75	75.4	0.415
		88,900	Yes	74.6	75.1	0.497
			No	75.3	76.7	0.35
		103,700	Yes	74.6	75.3	0.518
			No	75.2	75.4	0.153
	2	74,100	Yes	73.9	74.8	0.69
			No	74.9	75.1	0.233
		88,900	Yes	75.1	75.4	0.049
			No	76.3	75.8	-0.534
		103,700	Yes	75.8	75.5	-0.325
			No	76.2	75.7	-0.49
	3	74,100	Yes	72.7	73.7	0.98
			No	73.2	73.8	0.675
		88,900	Yes	72.7	73.5	0.76
			No	74.5	74.6	0.126
		103,700	Yes	74.4	74.4	-0.131
			No	75.8	75.3	-0.49
2012	1	74,100	Yes	70.9	71.4	0.55
			No	72.6	72.8	0.465
		88,900	Yes	70.6	71.1	0.76
			No	71.5	72.6	1.05
		103,700	Yes	70.8	71.2	0.4
			No	72.4	73.5	1.125
	2	74,100	Yes	70.9	71.9	1.05
			No	72.8	73.2	1.072
		88,900	Yes	72	72.6	1.118
			No	72.1	73.6	1.459
		103,700	Yes	73	75.3	2.349
			No	73	75.2	2.445
	3	74,100	Yes	69.1	69.4	0.541
			No	70.3	71	0.7
		88,900	Yes	70.9	71.4	0.828
			No	71.3	72.7	1.375
		103,700	Yes	68.9	70	1.125
			No	71.1	72.8	1.69

Table 10. Hybrid, seeding rate, and starter fertilizer effects on time to root characteristics at the V2 samplings at Ames, IA in 2011 and 2012.

Year	Hybrid	Seeding rate	Starter fertilizer	Root length	Surface area	Root diameter	Root tips	Root forks	Root biomass	Shoot biomass
2011	1	74,100	Yes	55.8	8.3	0.4852	295.75	110.7	0.1241	0.09677
			No	46.1	7.2	0.5087	251.34	91.2	0.1253	0.08975
		88,900	Yes	54.2	8.4	0.4952	299.69	100.5	0.1292	0.09628
			No	45.2	7.3	0.5328	238.75	92.9	0.1349	0.1049
		103,700	Yes	50.4	8	0.5221	236.55	100.7	0.1265	0.07998
			No	52.1	8.7	0.5423	257.9	100.8	0.1261	0.08663
	2	74,100	Yes	51.9	8.1	0.5094	250.25	108.5	0.1086	0.08358
			No	54.5	7.9	0.4703	303.79	97.3	0.1119	0.08333
		88,900	Yes	44.3	6.9	0.4956	235.3	82.3	0.1159	0.07478
			No	47.6	7.7	0.5236	229.07	96.4	0.1181	0.09771
		103,700	Yes	43.1	6.7	0.5392	228.52	84.3	0.1162	0.08422
			No	47	7.5	0.5143	243.75	89.7	0.1146	0.08991
	3	74,100	Yes	53.5	8.1	0.487	273.9	98.4	0.1335	0.1081
			No	47.3	7.3	0.512	239.4	93.2	0.1214	0.08186
		88,900	Yes	47.6	7.1	0.4839	247.25	94.7	0.1225	0.08534
			No	49.2	7.5	0.4988	262.9	97.2	0.1389	0.09376
		103,700	Yes	56.9	8.4	0.4806	314.9	106.3	0.1333	0.09699
			No	47.8	7.2	0.4864	235.95	99.9	0.1254	0.09113
2012	1	74,100	Yes	72.9	10.6	0.4642	376.65	133.7	0.1165	0.285
			No	67.5	9.4	0.449	346.35	113.6	0.09185	0.2304
		88,900	Yes	70.4	10	0.4609	348.5	119	0.0976	0.2638
			No	71.8	10.5	0.4701	351	114.3	0.0979	0.282
		103,700	Yes	60.7	9.2	0.4965	300.01	104.4	0.08988	0.2443
			No	61.6	8.9	0.4608	324.5	103.4	0.09475	0.274
	2	74,100	Yes	71.9	11	0.4834	351.8	124.5	0.1008	0.3432
			No	67.2	9.2	0.4518	362.4	109.3	0.09215	0.2651
		88,900	Yes	68	10	0.4727	361.7	105.6	0.1021	0.2876
			No	66.3	9.6	0.458	321.91	98.5	0.08667	0.2286
		103,700	Yes	69.6	9.7	0.4629	392.6	118	0.09875	0.2808
			No	63.2	8.8	0.4476	356.05	104.5	0.08995	0.2468
	3	74,100	Yes	54	8	0.4796	250.61	83	0.09024	0.2857
			No	57	8	0.4551	276.35	85.4	0.08045	0.224
		88,900	Yes	55	7.9	0.4568	282.85	73.7	0.08415	0.2406
			No	69.9	10.4	0.4739	334.65	105.5	0.09455	0.2081
		103,700	Yes	61.6	9.1	0.4748	292.5	84.9	0.09265	0.2605
			No	65.4	9	0.4491	341.5	112	0.09035	0.2281

Table 11. Hybrid, seeding rate, and starter fertilizer effects on time to root characteristics at the V4 samplings at Ames, IA in 2011 and 2012.

Year	Hyb	Seeding rate	SF†	Root length	Surface area	Root diameter	Root tips	Root forks	Root biomass (g·plant^{-1})	Shoot biomass (g·plant^{-1})
2011	1	74,100	Yes	89.9	16.7	0.5971	296.4	153.7	0.2281	0.9461
			No	98.1	18.5	0.5993	307.5	164.55	0.2062	0.7433
		88,900	Yes	108.9	20	0.5916	360.5	186.9	0.2649	0.9997
			No	97.2	17.5	0.5655	317.2	164.95	0.1187	0.7204
		103,700	Yes	93.3	17.4	0.5969	302.6	160.6	0.2274	0.921
			No	79.8	14.7	0.5948	249.7	132	0.1717	0.6772
	2	74,100	Yes	95.4	19	0.634	332.0	160.3	0.2741	1.1554
			No	92.3	17.3	0.6075	325.4	158.4	0.2161	0.8719
		88,900	Yes	88.4	16.6	0.6033	303.2	152.35	0.237	1.077
			No	91.9	16.7	0.5818	328.9	156.55	0.1897	0.7621
		103,700	Yes	80	15	0.5944	280.1	128.95	0.2008	0.7791
			No	82	14.6	0.5682	292.7	135.8	0.1829	0.7118
	3	74,100	Yes	94.9	18.5	0.6145	310.3	157.2	0.2502	1.0022
			No	106.6	19.9	0.6114	339.8	195.6	0.2437	1.0926
		88,900	Yes	102.6	18	0.5604	354.6	191.55	0.2339	0.8118
			No	88	15.9	0.5791	292.3	135.45	0.2045	0.8195
		103,700	Yes	81.3	13.7	0.5381	273.7	139.9	0.1861	0.6417
			No	86.6	15.4	0.5748	268.9	136.85	0.1881	0.7691
2012	1	74,100	Yes	82.1	15.6	0.6013	325.5	163.75	0.2338	1.0295
			No	76.2	14.4	0.5945	298.6	155.2	0.2003	0.747
		88,900	Yes	81.7	14.5	0.577	320.3	157	0.2373	1.057
			No	80	14.7	0.5913	326.4	150.35	0.1962	0.823
		103,700	Yes	71.7	13.3	0.5978	290.8	147.7	0.2168	0.9505
			No	73.3	12.7	0.562	297.3	145.8	0.1686	0.688
	2	74,100	Yes	77.5	14.4	0.6	329.0	150.85	0.2231	0.981
			No	66.1	13.3	0.6338	256.8	138.8	0.1639	0.7215
		88,900	Yes	79.7	14.6	0.5987	365.0	159.05	0.2331	0.973
			No	83.1	14.5	0.5718	357.15	174.6	0.1809	0.736
		103,700	Yes	72.5	12.6	0.5633	310.0	142.25	0.161	0.634
			No	72.1	11.8	0.5492	319.8	127.35	0.1493	0.589
	3	74,100	Yes	66.1	12.2	0.5958	252.1	124.25	0.2056	0.8915
			No	73.7	13	0.5816	304.8	142.5	0.2047	0.925
		88,900	Yes	75.7	12.4	0.5375	307.9	133.2	0.1735	0.647
			No	62.1	10.2	0.5239	246.0	111.15	0.1255	0.4675
		103,700	Yes	72.9	12.7	0.5698	264.3	136.15	0.1859	0.958
			No	76.6	12.9	0.5418	288.8	140.3	0.1529	0.5515

†SF = Starter fertilizer
‡Hyb = Hybrid

Table 12. Hybrid, seeding rate, and starter fertilizer effects on shoot characteristics including height and stem diameter at the samplings at Nashua, IA in 2011 and 2012.

Year	Hybrid	Seeding rate	Starter fertilizer	Height V3 (cm)	Height V9 (cm)	Height R2 (cm)	Stem diameter V3 (mm)	Stem diameter V9 (mm)	Stem diameter R2 (mm)
2011	1	74,100	Yes	19.53	46.69	101.43	5.39	24.21	24.17
			No	14.7	38.89	100.05	3.95	22.88	24.89
		88,900	Yes	17.14	41.58	98.38	4.23	22.64	23.26
			No	17.62	43.86	101.8	4.46	22.37	23.18
		103,700	Yes	21.13	50.54	103.6	5.9	25.1	23.91
			No	17.26	45.09	100.18	4.32	22.05	21.53
	2	74,100	Yes	20.53	45.94	104.65	5.15	25.73	25.15
			No	19.74	44.6	103.85	5.4	25.59	24.99
		88,900	Yes	19.09	43.21	101.3	4.9	23.77	23.37
			No	18.54	43.87	105.32	4.91	24.64	23.55
		103,700	Yes	17.83	41.09	101.4	4.61	23.07	21.94
			No	19.21	44.74	105.32	5.04	23.54	22.64
	3	74,100	Yes	17.45	45.2	104.18	4.46	26.2	26.58
			No	17.03	42.81	103.6	4.35	24.47	26.44
		88,900	Yes	19.34	48.95	105.48	5.02	25.55	26.03
			No	17	42.41	99.85	4.26	23.82	24.75
		103,700	Yes	18.37	47.49	100.8	5	23.97	23.43
			No	16.07	43.08	100.95	4.11	22.63	22.97
2012	1	74,100	Yes	22.95	52.29	90.7	5.74	24.36	22.28
			No	19.88	48.08	87.7	4.77	23.23	21.6
		88,900	Yes	21.65	50.78	88.93	5.83	23.01	20.67
			No	20.11	48.25	88.78	5.1	21.96	20.19
		103,700	Yes	22.71	52.78	89.25	5.9	22.14	20.14
			No	20.8	49.01	87.55	4.99	21.45	19.43
	2	74,100	Yes	22.26	48.88	93	5.84	25.7	23.08
			No	20.3	45.63	90.8	5.13	23.74	21.88
		88,900	Yes	21.28	47.29	91.73	5.47	23.2	21.15
			No	18.94	43.11	87.83	4.7	22.46	20.03
		103,700	Yes	23.75	48.98	87.53	5.88	22.87	19.68
			No	18.83	43.99	87.28	4.92	21.999	19.84
	3	74,100	Yes	22.03	50.99	91.88	5.64	25.04	22.99
			No	20.48	47.4	89.3	4.96	23.78	22.21
		88,900	Yes	21.74	50.65	89.15	5.14	23.38	20.99
			No	20.41	47.95	85.9	4.86	22.52	20.5
		103,700	Yes	21.79	49.28	88.5	5.18	22.33	20.43
			No	19.14	45.59	85.98	4.28	21.39	19.86

Table 13. Hybrid, seeding rate, and starter fertilizer effects on average estimated biomass across biomass samplings at Nashua, IA. Biomass was estimated using models developed through destructive sampling of 360 plants per sampling date utilizing height and stem diameter measurements that were then correlated to biomass.

				Estimated plant biomass (g·plant^{-1})		
Year	Hybrid	Seeding rate	Starter fertilizer	V3	V9	R2
2011	1	74,100	Yes	0.29	27.33	157.91
			No	0.15	18.95	164.1
		88,900	Yes	0.21	21.66	145.73
			No	0.22	22.76	145.11
		103,700	Yes	0.34	31.75	156.64
			No	0.21	24.4	129.99
	2	74,100	Yes	0.29	28.09	171.89
			No	0.29	26.58	167.91
		88,900	Yes	0.25	23.29	148.4
			No	0.25	25.33	154.55
		103,700	Yes	0.22	20.81	133.82
			No	0.27	24.82	144.91
	3	74,100	Yes	0.21	27.97	186.44
			No	0.2	23.77	184.81
		88,900	Yes	0.27	30.58	181.04
			No	0.2	23.71	165.57
		103,700	Yes	0.25	28.13	148.3
			No	0.18	22.88	145.39
2012	1	74,100	Yes	0.54	39.36	181.05
			No	0.4	32.65	169.36
		88,900	Yes	0.51	34.84	156.14
			No	0.42	30.34	148.78
		103,700	Yes	0.55	34.87	148.61
			No	0.44	30.09	137.55
	2	74,100	Yes	0.54	40.35	195.03
			No	0.44	32.54	176.34
		88,900	Yes	0.48	32.14	165.13
			No	0.37	26.77	147.06
		103,700	Yes	0.59	33.35	141.53
			No	0.38	26.31	144.73
	3	74,100	Yes	0.52	40.31	192.94
			No	0.43	33.39	179.9
		88,900	Yes	0.48	35.82	161.31
			No	0.43	31.19	152.34
		103,700	Yes	0.48	32.17	152.68
			No	0.36	26.69	143.09

Table 14. Hybrid, seeding rate, and starter fertilizer effects on average plant stage of tagged plants at vegetative samplings at Nashua, IA in 2011 and 2012.

Year	Hybrid	Seeding rate	Starter fertilizer	V3	V9
2011	1	74,100	Yes	3.11	8.6
			No	2.74	8.04
		88,900	Yes	2.82	8.06
			No	3.02	8.28
		103,700	Yes	3.21	8.61
			No	2.92	8.26
	2	74,100	Yes	3.06	8.57
			No	3.15	8.78
		88,900	Yes	3.14	8.65
			No	3.09	8.52
		103,700	Yes	2.99	8.38
			No	3.1	8.34
	3	74,100	Yes	2.93	8.09
			No	2.91	8
		88,900	Yes	3.09	8.19
			No	2.93	7.87
		103,700	Yes	3.04	8.13
			No	2.79	7.78
2012	1	74,100	Yes	3.32	9.63
			No	3.14	9.2
		88,900	Yes	3.35	9.36
			No	3.14	8.99
		103,700	Yes	3.35	9.33
			No	3.23	9.01
	2	74,100	Yes	3.32	9.66
			No	3.21	9.12
		88,900	Yes	3.26	9.33
			No	3.23	9.09
		103,700	Yes	3.41	9.35
			No	3.21	8.97
	3	74,100	Yes	3.28	9.24
			No	3.2	8.83
		88,900	Yes	3.28	9.08
			No	3.2	8.76
		103,700	Yes	3.28	8.96
			No	3.09	8.48

Table 15. Hybrid, seeding rate and starter fertilizer effects on grain yield and moisture at Nashua, IA in 2011 and 2012.

Year	Hybrid	Seeding rate	Starter fertilizer	Grain yield ($Mg \cdot ha^{-1}$)	Grain moisture
2011	1	74,100	Yes	12.36849	18.88
			No	11.87571	18.93
		88,900	Yes	12.3823	19.13
			No	12.60515	19.2
		103,700	Yes	13.31262	19.3
			No	13.07282	19.34
	2	74,100	Yes	12.56309	18.6
			No	12.95857	18.45
		88,900	Yes	13.6516	18.4
			No	13.23792	18.85
		103,700	Yes	13.65035	18.63
			No	13.03013	19.08
	3	74,100	Yes	11.03829	19.15
			No	11.3484	19.1
		88,900	Yes	11.93409	19.18
			No	12.47207	19.25
		103,700	Yes	11.99874	19.4
			No	12.43252	19.35
2012	1	74,100	Yes	10.11551	14.58
			No	8.787194	14.33
		88,900	Yes	10.43691	14.73
			No	8.805399	15.2
		103,700	Yes	9.601381	14.8
			No	8.710609	15.25
	2	74,100	Yes	10.03955	14.7
			No	8.973007	14.95
		88,900	Yes	10.27307	14.93
			No	8.550534	15.2
		103,700	Yes	7.998117	14.73
			No	9.069052	15.18
	3	74,100	Yes	10.91463	15.53
			No	9.812932	15.65
		88,900	Yes	10.21532	15.68
			No	8.817326	15.55
		103,700	Yes	9.295041	15.85
			No	9.424984	15.95

Table 16. Hybrid, seeding rate and starter fertilizer effects on grain yield components at Nashua, IA in 2011 and 2012.

Year	Hybrid	Seeding rate	Starter fertilizer	Kernel rows ear^{-1}	Kernel number	Plant moisture	Plant yield (g·plant^{-1})
2011	1	74,100	Yes	15.9	583.45	22.68	189.93
			No	15.74	553.07	22.52	188.1
		88,900	Yes	15.69	548.58	24.48	174.75
			No	16	529.98	23.88	161.56
		103,700	Yes	15.49	582.12	22.73	181.31
			No	16.06	467.7	25.49	141.29
	2	74,100	Yes	17.53	562.38	24.34	177.72
			No	16.88	560.41	24.24	179.87
		88,900	Yes	16.33	509.28	25.1	156.16
			No	17.01	522.61	24.95	156.11
		103,700	Yes	16.67	462.41	27.21	138.77
			No	16.72	460.44	26.6	133.66
	3	74,100	Yes	16.15	604.96	21.34	206.78
			No	16.25	613.45	21.97	198.55
		88,900	Yes	16.45	624.58	21.83	194.15
			No	15.87	565.77	23.52	182.99
		103,700	Yes	15.95	514.75	23.38	162.69
			No	15.9	538.98	24.26	162.34
2012	1	74,100	Yes	15.85	471.43	12.99	139.44
			No	14.68	388.55	15.12	114.6
		88,900	Yes	15.6	386.73	14.77	116.08
			No	14.85	340.47	14.65	99.88
		103,700	Yes	15.03	326	14.68	98.24
			No	14.7	298.03	14.57	86.49
	2	74,100	Yes	15.91	457.47	15.24	139.42
			No	14.95	412.41	16.2	122.55
		88,900	Yes	14.3	381.97	16.22	118.21
			No	13.17	334.71	17.82	98.52
		103,700	Yes	13.41	318.81	15.85	91.83
			No	13.47	304.94	18.24	89.38
	3	74,100	Yes	15.7	522.02	15.36	149.2
			No	15.21	473.6	15.95	141.97
		88,900	Yes	15.44	449.62	15.64	119.93
			No	14.96	369.69	15.74	101.37
		103,700	Yes	15.34	399.34	166.37	109.94
			No	15.14	355.43	16.72	97.78

Table 17. Hybrid, seeding rate and starter fertilizer effects on estimated biomass coefficient of variation (CV). Biomass was estimated using models developed through destructive sampling of 360 plants per sampling date utilizing height and stem diameter measurements that were then correlated to biomass. Nashua, IA 2011 and 2012.

				Estimated biomass CV		
Year	Hybrid	Seeding rate	Starter fertilizer	V3	V9	R2
2011	1	74,100	Yes	44.6	27.6	25.7
			No	53.4	46.5	30.3
		88,900	Yes	53.4	40.2	31.8
			No	27.6	17.6	15.3
		103,700	Yes	40.3	26.6	27.4
			No	35	29.3	28.4
	2	74,100	Yes	43.7	31	26
			No	33.4	27.7	22.1
		88,900	Yes	32.8	34.9	28.5
			No	41	32.8	22.5
		103,700	Yes	36.6	30.5	22.3
			No	36.4	28.8	23.6
	3	74,100	Yes	41.9	28.2	20.3
			No	44	32.2	23.6
		88,900	Yes	40.6	24.6	18.8
			No	41.8	40.2	35.4
		103,700	Yes	40.8	28.8	27.1
			No	54	38.1	32.5
2012	1	74,100	Yes	23	18.3	17.7
			No	32	24.5	18.8
		88,900	Yes	24.9	19.5	19.4
			No	27.3	24.2	24.2
		103,700	Yes	27.4	14.7	19.3
			No	22.3	21.8	21.4
	2	74,100	Yes	36.4	26.3	19.3
			No	36.5	28.7	25.9
		88,900	Yes	33.6	23.7	22.7
			No	35.5	31.8	29.1
		103,700	Yes	30.6	27.5	25.5
			No	43.6	28.2	26.1
	3	74,100	Yes	30.5	22.4	21
			No	23.7	24.7	23.7
		88,900	Yes	28	26.3	24.2
			No	24.5	19.6	21.1
		103,700	Yes	27.1	23.1	22.9
			No	28.7	22.9	21.4

Table 18. Hybrid, seeding rate, and starter fertilizer effects on early- and late-season populations and plant spacing standard parameters. Nashua, IA 2011 and 2012.

Year	Hybrid	Seeding rate	Starter fertilizer	Early-season population	Late-season population	Spacing standard deviation	Average spacing
2011	1	74,100	Yes	48010.625	93551.25	4.0742	9.1041
			No	47701.875	86141.25	6.7599	10.3125
		88,900	Yes	54340	94168.75	3.5325	8.6667
			No	65918.125	86450	2.3019	6.6667
		103,700	Yes	67770.625	94477.5	3.9198	7.8958
			No	73945.625	86758.75	3.5118	6.1667
	2	74,100	Yes	63139.375	77805	2.7649	7.5834
			No	66998.75	77496.25	2.6738	7.7709
		88,900	Yes	76415.625	84906.25	2.639	6.625
			No	76724.375	75643.75	3.2847	6.8996
		103,700	Yes	85060.625	77805	2.8314	6.3731
			No	90926.875	87376.25	2.1238	5.75
	3	74,100	Yes	42761.875	98800	5.037	10.2443
			No	43379.375	83362.5	5.6298	10.75
		88,900	Yes	53568.125	94168.75	4.3511	9.3845
			No	53876.875	94477.5	4.5169	9.0625
		103,700	Yes	59588.75	82436.25	2.6732	6.9407
			No	58662.5	83053.75	4.0763	6.8958
2012	1	74,100	Yes	73482.5	71938.75	2.6714	7.2917
			No	73791.25	71321.25	2.4217	7.375
		88,900	Yes	65763.75	82436.25	2.568	6.3333
			No	69777.5	86758.75	2.7285	6.4375
		103,700	Yes	67307.5	97873.75	2.5614	5.3958
			No	72865	100652.5	1.3788	5.125
	2	74,100	Yes	74100	69468.75	4.0647	7.9432
			No	78731.25	71630	2.8464	7.375
		88,900	Yes	69468.75	80892.5	2.597	6.625
			No	80583.75	83980	2.2642	5.9167
		103,700	Yes	79966.25	97873.75	1.3386	5.0208
			No	62367.5	94786.25	2.0285	5.3049
	3	74,100	Yes	69777.5	70086.25	2.5287	7.9375
			No	84288.75	66998.75	1.7765	7.3333
		88,900	Yes	70086.25	82436.25	2.0364	6.375
			No	80892.5	84597.5	1.8366	6.0625
		103,700	Yes	65146.25	95095	2.6104	6.1458
			No	72556.25	95712.5	1.9575	5.25